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Milton K. Pigg
and
James B. Burton

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46

by

Milton K. Pigg

Major, Corps of Engineers, United States Army

and

James B. Burton

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

A study of the influence of the electrodes, discharge length, current, and a magnetic field on the characteristics of moving and standing striations in a low pressure DC argon glow discharge indicated that the cathode was of major importance. The anode evidently had little or no effect. Changes in discharge tube current and discharge length merely expanded or compressed the striation responses in time and/or in space; the sequence of events was not altered. The magnet produced a local effect in the vicinity of the magnet similar to an increased discharge length.

All observations were made at a pressure of two mm of mercury with an H shaped tube containing four electrodes. Standing and moving striations both were always evident when a stable operating mode was present. There was, then, the rather unusual situation of moving striations moving through standing striations always present. It was found that the moving striations seemed to have a maximum velocity just before they reached the head (cathode side) of a standing striation, and a minimum velocity immediately after passing through the head of the standing striation.

A very strong indication was found of a phase difference of from 0 to 15 microseconds between the 7500 A° lines (red) and the 4200 A° lines (blue) of the moving striations, with the ~~red~~ blue line appearing first. This result appears to be contrary to extant theory and previous results at 12 mm of argon.

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I. INTRODUCTION

1. Summary

This experimental investigation is essentially a further development of the project initiated at the U. S. Naval Postgraduate School by Karge, Hooks, and Oleson in 1955 (13), and continued last year by Kolkhorst and Strong (14).

Through use of photomultiplier and oscillographic photography techniques, stationary and moving striations were studied in the positive column of a direct current argon glow discharge at 2 mm pressure. The moving striations moved from anode to cathode at acoustic speeds, passing through the standing striae (6). Eleven different combinations of electrodes were used, in conjunction with a "long" and a "short" discharge path, to determine the effect of electrodes and relative tube lengths, as well as other tube parameters, on striations.

The motion and variations in light intensity of the positive striations were studied using spectroscopic techniques in order to observe the relative behavior of particles excited to various energy levels. Also several sets of observations were made using a small Alnico horseshoe magnet adjacent to the central portion of the positive column.

Finally, stroboscopic visual observations of the positive column with a rotating slotted disk were made in order to further substantiate oscillographic indications of wavelength relationships between the stationary and moving striae. Visual observations, using a rotating mirror arrangement, were made of the standing striations as they were being traversed by the moving striae; and color photographs (time exposures) were made of the standing striae.

Comparison of results with pertinent available theory was attempted (7, 12, 22, 25).

2. The Glow Discharge

When a gradually increasing voltage is applied across two electrodes in a gas, only an extremely small current flows until the applied potential reaches a critical value called the "breakdown potential". At this point, the current increases by a large factor - possibly as much as 10^8 - and the subsequent transport of electricity is accompanied by a characteristic color and shape of light emission called a "glow discharge".

At atmospheric pressure, the discharge takes the form of a tortuous spark and is essentially the natural phenomenon of lightning. As the pressure of the gas is reduced, the breakdown potential required also decreases and the conducting path becomes thicker and more diffuse. At a pressure of a few cm. of Hg the glow will, in most cases, be uniform and occupy the entire container. At a pressure of a few mm of Hg striations of brighter light become evident. Both standing and moving striations are generally observed to occur in the positive column, although the moving striations may extend throughout the tube to both electrodes. Figure 1 depicts the characteristic areas of a glow discharge in a typical discharge tube.

3. History

Until recently it has been felt that the simplest conditions which can prevail in a low pressure glow discharge are those in which the positive column is homogenous and the current is constant. Although both moving and stationary striations have been long known and evidently often noted, they have never acquired a stature beyond that of a mere curiosity; a manifestation, perhaps, of a somewhat abnormal situation (7). A summary of the early work in the field can be found in the paper by J. J. Thomson (23) and a summary of the more recent efforts is covered in the monograph by Emeleus (9), the review of Druyvesteyn and Penning (8), or in any

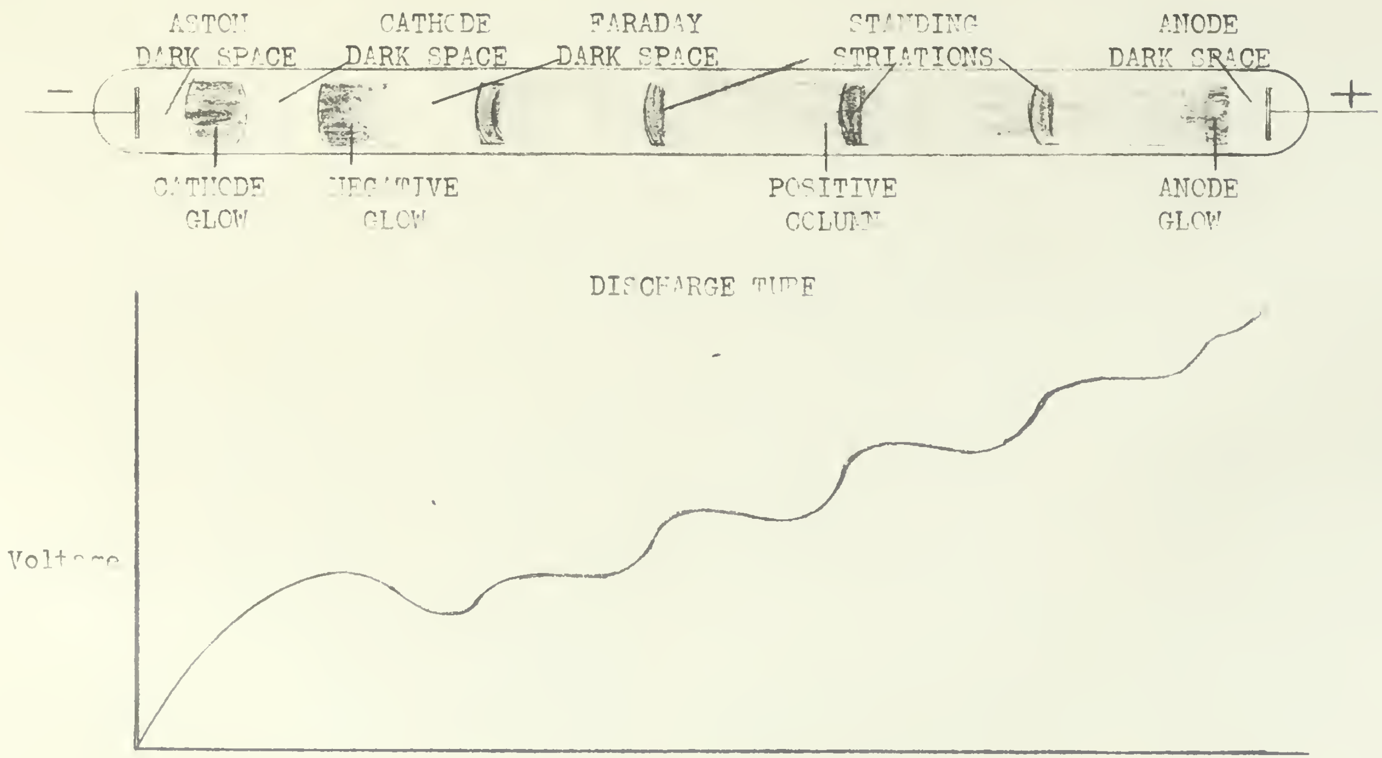


Figure 1. Regions of a Typical Discharge and Corresponding Voltage Changes

of the standard texts on the subject (3, 15, 24). Study of the moving striations has been made chiefly by means of rotating mirrors or by rotating cameras, although Pupp (20), who has made a rather extensive study of these phenomena, also used a photo cell in conjunction with a cathode-ray tube. Electrical oscillations accompanying the moving striations were the subject of investigations by Appleton and West (1), and by Fox (11). The standing striations have been investigated by means of probes and cathode rays shot transverse to the discharge (9).

4. Theories

It has just recently begun to be generally realized that striations are much more common in gaseous discharges, that is in the flow of electricity through a gas, than previously believed. In fact it has been observed that striations in a glow discharge are the rule rather than the exception and it is quite likely that any theory of discharges which neglects striations is defective in some essential way (7).

Theoretical explanations of any sort, however, concerning glow and striation phenomena, are conspicuous by their absence. No relationship even between moving striations and those of a stationary type has been proven generally satisfactory and acceptable (7).

At present there are two major theories of striation phenomena, in both of which are large areas of "terra incognita". The first is that of the Russian physicist G. V. Gordeev (12). A detailed summary of the theory is somewhat beyond the scope of this paper, being of a highly obstruse mathematical nature, and being further complicated by confusion of technical and mathematical terms in the available translation. Two of Gordeev's more recent papers on the subject are now being translated and may clarify some points. However, they are not yet available to the authors.

Gordeev notes that there is a high frequency oscillation of electrons

in the glow at all times, and proposes that these oscillations are formed into "wave groups" by electromagnetic reflections and interactions. The electron stream from the cathode strikes the anode, reflecting back a disturbance in the electron oscillatory motion as a "falling" wave group. This disturbance may again be reflected from the cathode as a "repelled" wave group. In brief, if the "repelled" waves are repelled in the proper phase with the "falling" waves, we obtain a "standing" striation. If the phase relationship is not proper for striations we get a homogenous plasma. If the "repelled" waves are rapidly damped we get moving striations from anode to cathode comprising only the "falling" waves. The latter case has a further permutation. If the "falling" waves have a group velocity of zero, we obtain instead of moving striations, "stationary" striations with the distance between striae being the phase length of the waves. Thus there are two varieties of stationary strata: 1) where the group velocity is equal to zero; and 2) when a node or "standing" wave is formed.

Donahue and Dieke (7) also note "falling" waves (positive striations) and "repelled" waves (negative striations) but, with various other experimental physicists in this country and England (10, 21, 22), connect the positive striations with the motion of positive ions, and the negative striations with the motion of electrons. The proposals of Donahue and Dieke constitute possibly the most coordinated theory of moving striations now extant.

In mercury vapor, assuming the existence of a positive striation in the positive column near the anode, plasma electrons may produce a layer of metastables to the cathode side of the positive striation. The next group of electrons will ionize and excite the metastable layer, producing a

positive space charge strata. Electrons which gain energy in the field of the positive space charge layer will then repeat the process, moving the striation one step nearer the cathode. The previous layer of ions falls off due to normal dissipation effects such as lateral motion to the walls, recombinations, etc. Eventually the moving striation-ion group moves far enough from the anode for striation number two to form. In an instant, a series of positive striations may be electronically or stroboscopically detected, moving at speeds of the order of the speed of sound in the gas, from anode to cathode. Visual observation of the positive column at this time shows only what appears to be a homogeneous plasma.

Donahue and Dieke's hypothesis of the mechanism of the negative striation is a bit more complex. They note that the profile of the voltage from cathode to anode indicates a peak at the glow, with a subsequent negative slope at the anode end of the negative glow, a minimum at the head of the Faraday dark space, and a steady positive slope from there on to the anode as shown in Figure 1. The steps in the voltage curve in the region of the positive column are those shown by Emeleus (9). Poisson's equation,

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon_0}$$

applied to the negative slope at the anode end of the negative glow shows that there must be a concentration of negative charges, or electrons, at the anode end of the negative glow. Donahue and Dieke postulate that this "electron trap" cannot trap too many electrons or the glow would be extinguished, and therefore there must be some mechanism to relieve the congestion if diffusion is not sufficient. This mechanism is that of the moving positive striations noted earlier. When one of these striations, preceded by

a region of high field, has come sufficiently close to the trapped electrons, the potential barrier is lowered and the electrons are released to travel in a burst toward the positive striation. This burst of negative charges is a negative striation. When the electrons leave they apparently leave behind a positive space charge which begins at once to travel toward the cathode through the negative glow. The resulting increased cathode fall causes enhanced electron emission from the cathode, which is also termed a negative striation. This negative striation meets the slower positive space charge group at the head, or cathode edge, of the negative glow. There the positive and negative space charges tend to neutralize each other. The process of electron entrapment now begins again, because by this time the positive striation in the positive column has been neutralized by one of the negative striations which it drew out of the anode end of the negative glow. It is noted that one, two, or perhaps more negative striations may be extracted from the negative glow by a single positive striation.

In the positive column at pressures of the order of one millimeter, the electrons do not recombine to any great extent as they stop and neutralize the positive striation. If free electrons are available, succeeding positive striations extract or release them, and a series of negative striations may be detected moving through the discharge. Standing striations mark the meeting of the positive and negative striations. At these points the rate of excitation decreases because of a decline in the magnitude of the electric field due to space charge neutralization. In spite of this fact the light intensity appears to be a maximum because the two striations remain motionless together for

approximately 20 to 100 microseconds. The separation d_s of the stationary striations is related to the distance λ between the moving striations by

$$\lambda = nd_s$$

where n is an integer, usually one or two. The number of negative striations leaving the negative glow between the time two positive striations reach it determines the number of stationary striations per wavelength in the positive column. This is essentially the theory of Donahue and Dieke.

These theories raise the question as to whether or not it is reasonable that the ionization and excitation functions should have the same time and space dependence. A direct answer is perhaps not possible. However, the fact that a narrow range of electron energies is involved in the excitation and ionization that is observed does support the idea that the two functions should be similar. It seems probable that the changes in the electron energy distribution function that undoubtedly occur in the positive column do not change greatly the ratio of exciting to ionizing collisions (22).

A recent mathematical approach to a theory of the oscillating positive column is due to Watanabe and Oleson (25). They show that continuity equations (involving semi-empirical mobility constants) for positive ions and electrons coupled to each other by the Coulomb forces and the effect of ionizing collisions have a solution representing traveling density waves whose frequencies are widely different from the usual plasma oscillations. These solutions may provide a theoretical basis, with further refinement, for explaining moving striations. The basic assumption in the mathematical development was that there exists a Maxwellian distribution of electron and positive ion energies in the plasma, that the well

known ambipolar diffusion equation applies (3), and that the number of ion pairs created per unit time per one electron is a constant. The first two assumptions have been substantiated by other experimental physicists. The other basic assumption of the Watanabe and Oleson paper, that the proportion of ion and electron particles involved in the striation phenomena is very small compared with the total number of the respective particles present in the discharge, has apparently not been born out by experimental evidence (22). However, the latter assumption was admitted by them to be a mathematical expedient to linearize the equations, and not necessarily in strict accordance with reality.

II. APPARATUS AND EXPERIMENTAL TECHNIQUES

1. General

The apparatus and techniques were essentially those employed previously at the U. S. Naval Postgraduate School by Karge, Hooks, and Oleson (13) and by Kolkhorst and Strong (14) and at Johns Hopkins University by Donahue and Dieke (4, 5, 6, 7). The discharge tube and vacuum system were designed by Professor N. L. Oleson and manufactured by Mr. I. C. Dumas of the Stanford Research Institute.

Figure 2 is a schematic diagram of the equipment showing wiring used for voltage-light intensity observations. Figure 3 depicts actual arrangement of the equipment. Notable features are a dual beam oscillograph on which can be presented simultaneously two time dependent variables, a frequency counter permitting instantaneous and continuous frequency monitoring, and a glass prism spectrometer used for selecting spectral lines from the glow.

In order to obtain the highest possible degree of purity, degassing of the tube walls and electrodes was accomplished prior to filling the tube with argon gas. Before making any observations the gaseous discharge and the equipment were operated for periods of four hours to ensure stable operating conditions.

2. Discharge Tube

Details of the discharge tube are shown in Figure 4 and a photograph is included as Figure 5. It was made of pyrex glass and contained four electrodes (two of zirconium, one of molybdenum, and one of tungsten wire). There were thus eleven possible combinations of cathode and anode, some discharge paths being shorter (vertical only) than others

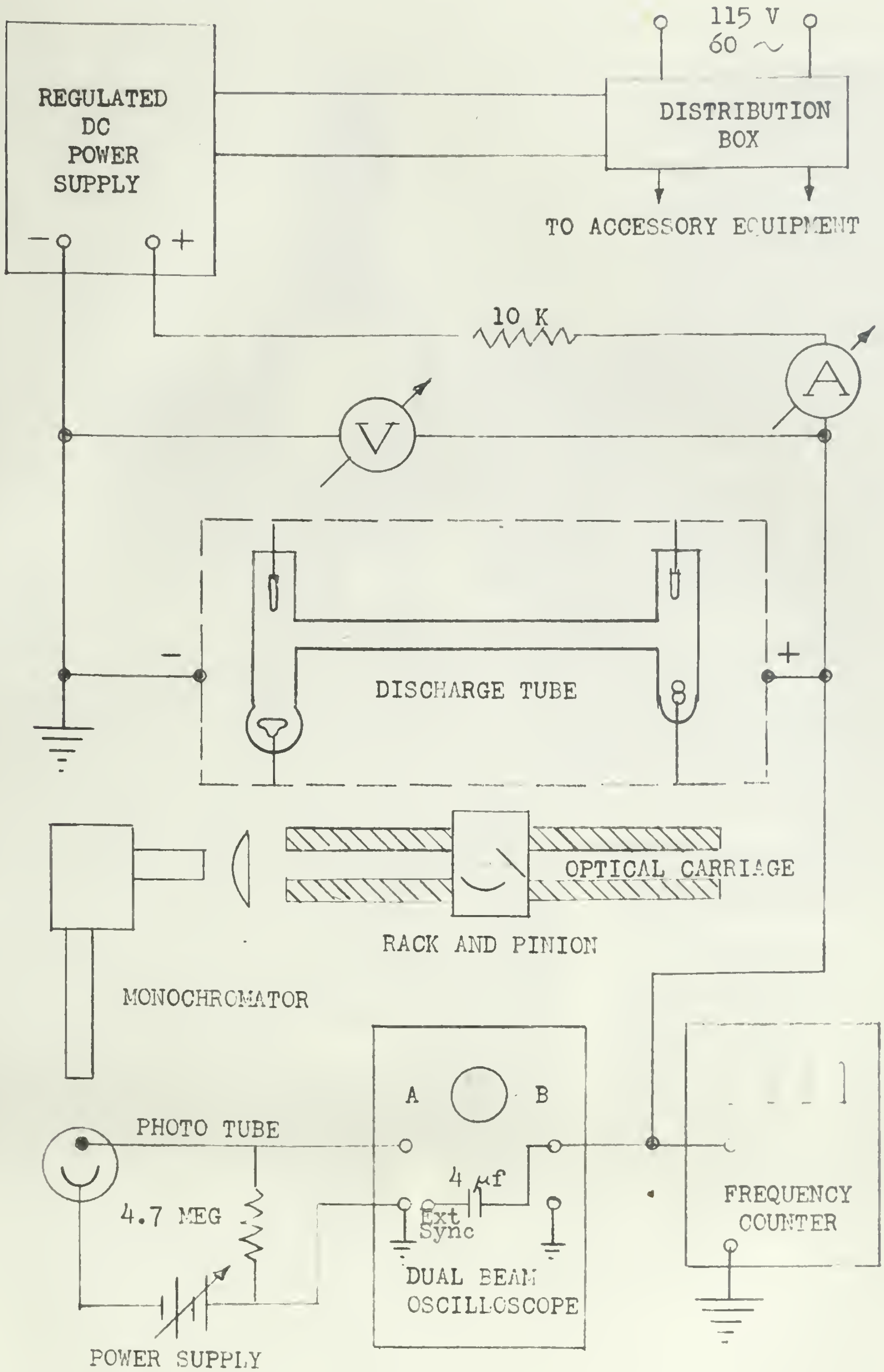


Figure 2

Schematic and Circuit Diagram for Voltage---

Light Intensity Observations

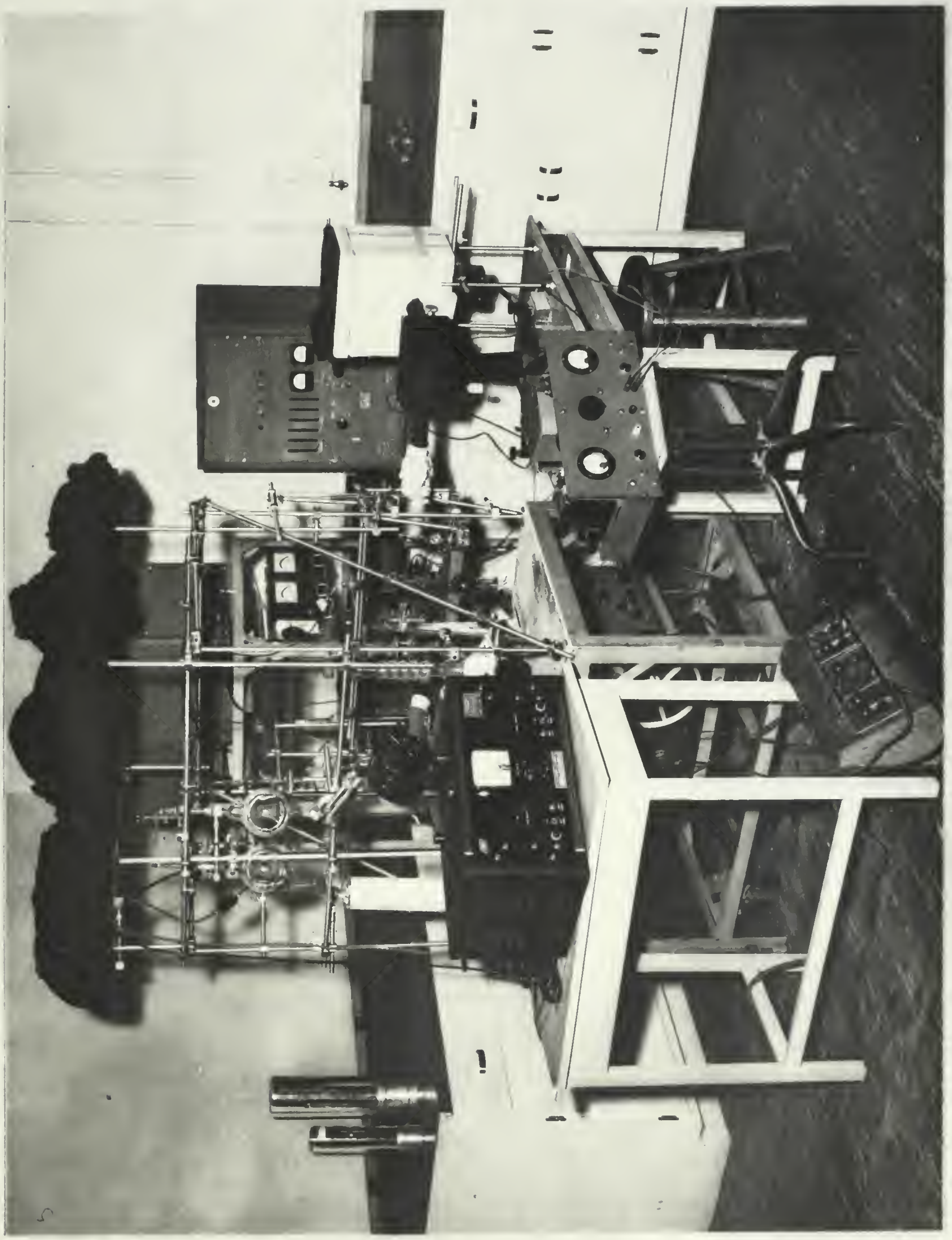


Figure 3

View of Equipment

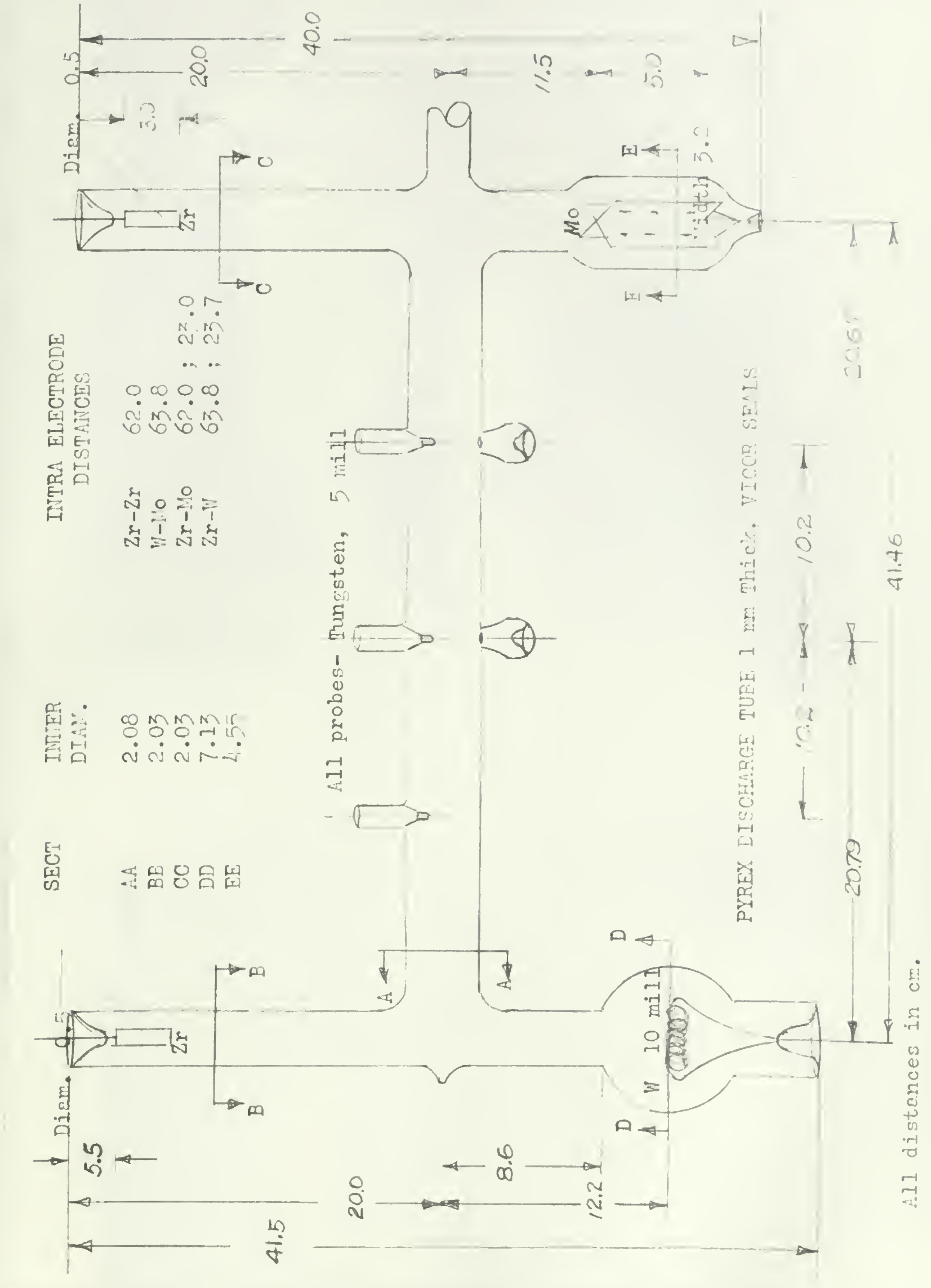


Figure 4

Details of Discharge Tube

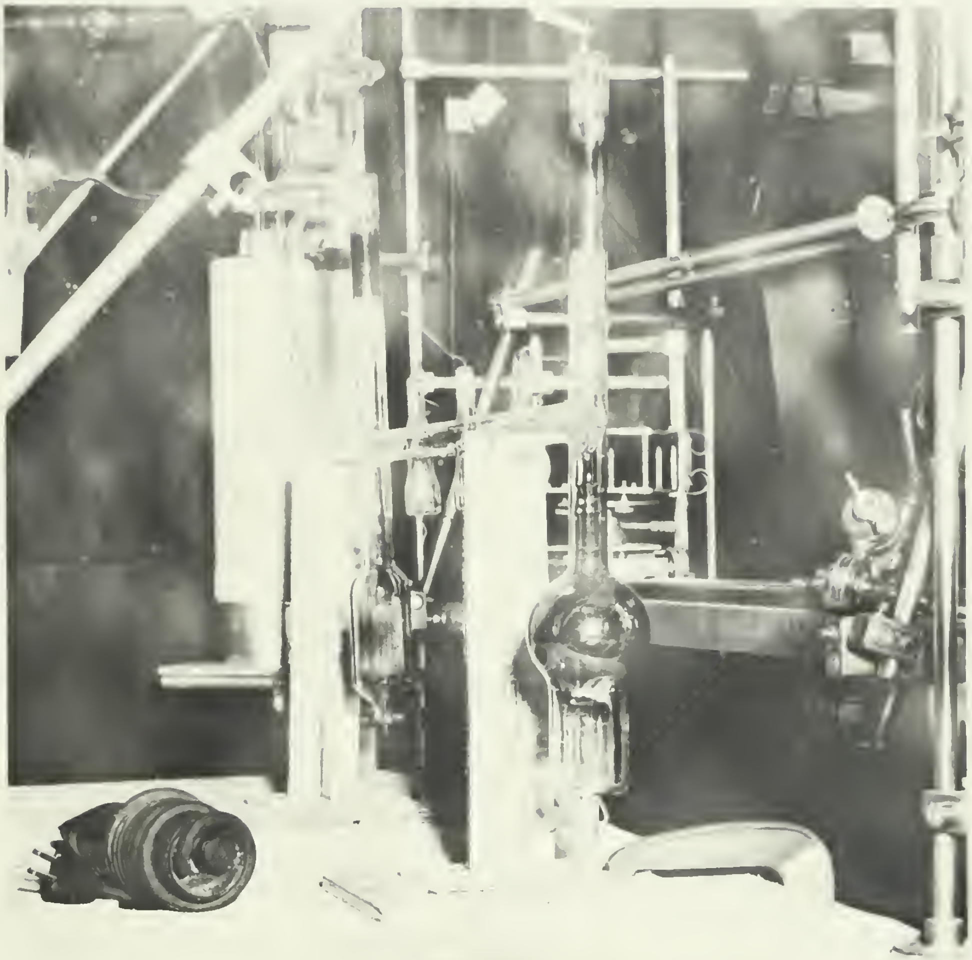


Figure 5. View of Discharge Tube

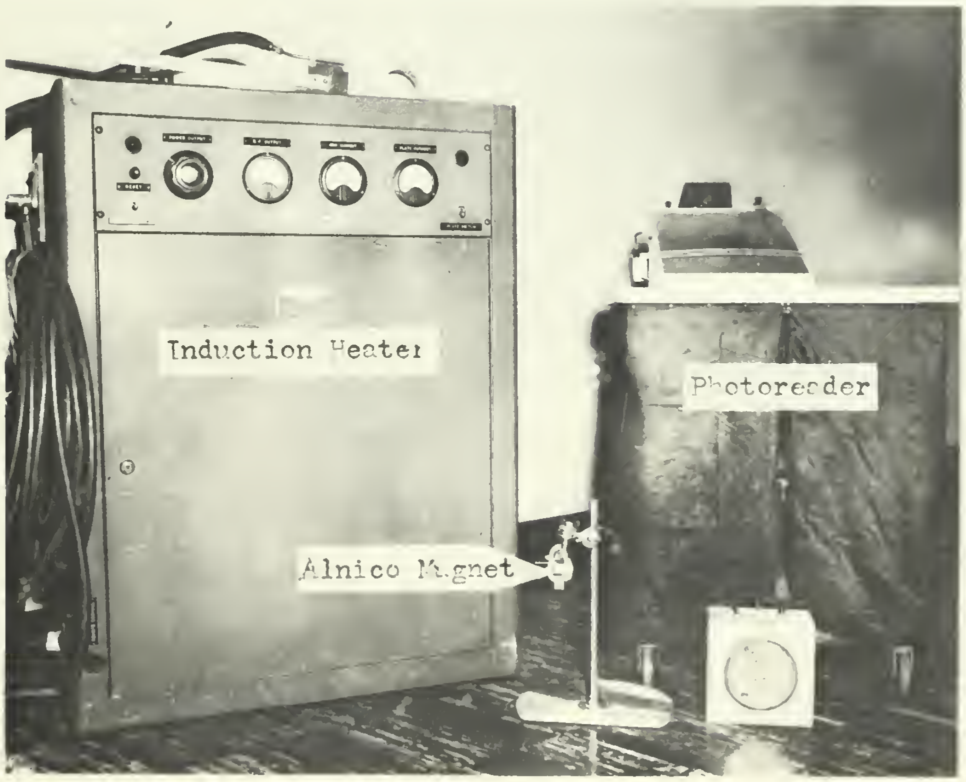


Figure 6. View of Auxiliary Equipment

(vertical and horizontal). The molybdenum electrode consisted of an arrangement of four fins and had a relatively large area of approximately 65 sq cm. The zirconium electrodes were cylindrical having an area of approximately 4.75 sq cm while the tungsten electrode was of 10 mil wire. All observations of light intensity, other than visual, were made in the center horizontal portion of the tube which contained a portion of the positive column.

The tube was equipped with five probes for field and concentration measurements. However, the probes were not used in this study.

The tube was connected to a high vacuum and filling system for use in degassing the tube and in filling with gas to the desired pressure. Degassing was accomplished under high vacuum by wrapping the tube with heating tapes and baking at about 400° C for four hours followed by heating of the electrodes to a cherry red with an induction heating generator. The tube and vacuum system were also flamed with a soft flame from a gas torch. A vacuum of 5×10^{-8} mm Hg was thus obtained. Prior to charging the tube it was flushed with a few millimeters of argon, and high current positive ion bombardment of the electrodes was carried out by using 1400 volts from a transformer across the electrodes. After having taken these steps to obtain a high degree of purity, the tube was filled to a pressure of two mm Hg using Linde high purity mass spectrometer controlled argon gas which had been passed through a liquid nitrogen trap.

3. Instrumentation

Oscillations in tube voltage and light intensity were observed simultaneously on the dual beam oscillograph shown in Figure 7. Both sweeps were triggered externally by the oscillations in tube voltage and were supplied by the same sweep voltage by means of placing the sweep selector

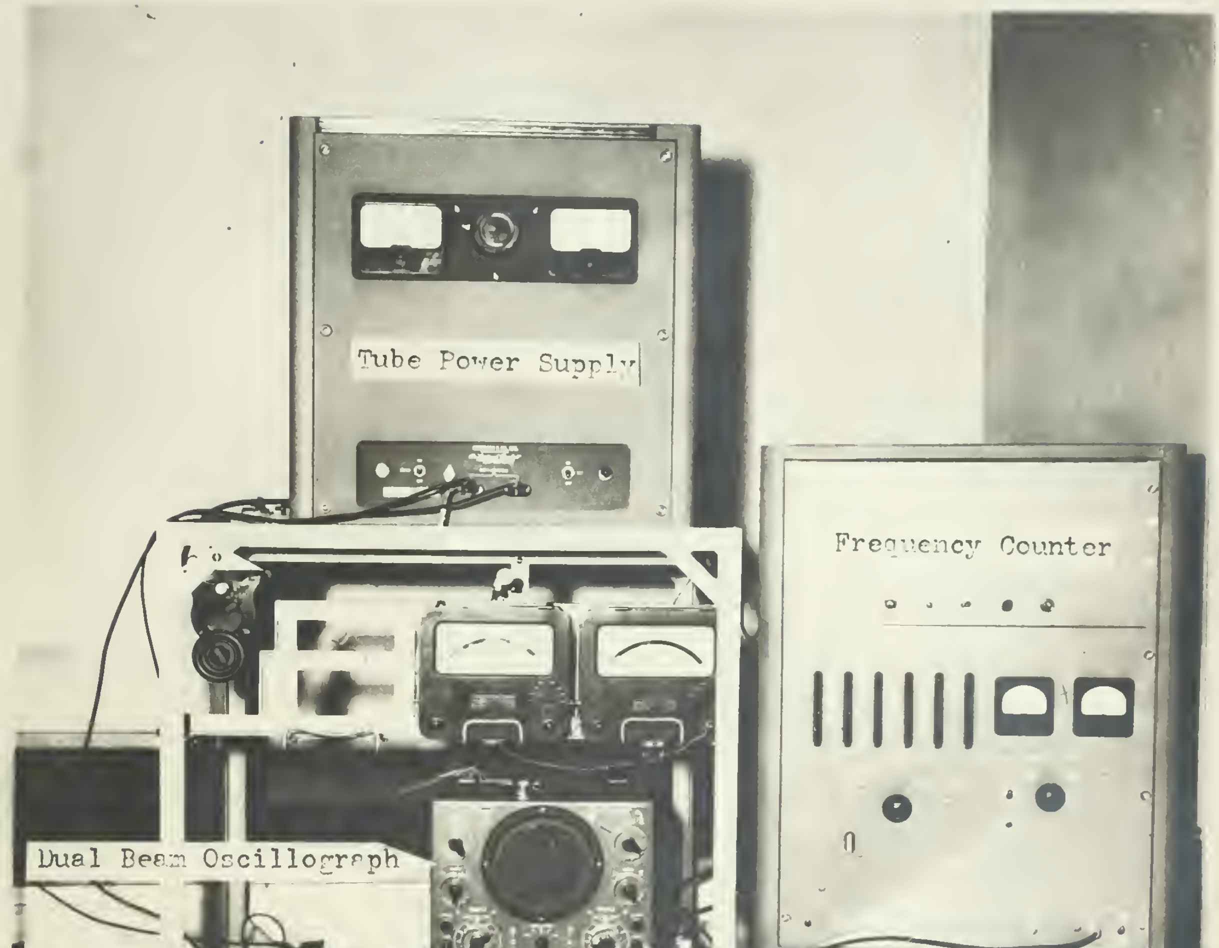


Figure 7

View of Instrumentation

switch in the "A common" position. External triggering was through a four micro-farad condenser. The signal was applied at the B input terminals of the dual beam oscillograph.

At a point in the discharge determined by the position of the optical carriage, it was possible to observe on a single oscilloscope variations in light intensity and tube voltage. These two traces were displayed simultaneously and on the same time scale.

A frequency counter was also triggered by the oscillations in tube voltage through a 10 micro-farad condenser. This provided an instantaneous and continuous indication of the frequency of the voltage oscillations being viewed on the oscilloscope. The frequency was found to be a very sensitive indication of the stability of the mode being observed.

The waveforms displayed on the oscillograph were, in most cases, photographed with an oscillograph camera (Figure 9) using Kodak Ortho-Linograph film and lens and shutter settings of f/2.8 and 1/37th second respectively. A zero reference on the photographs of the waveforms was obtained by a double exposure technique taking one exposure with the vertical amplifiers off followed by a second of the waveforms (vertical amplifiers on).

The indication of the frequency counter was verified by displaying the output of a sine wave generator on the oscillograph with the voltage oscillations. This was necessary because the frequency counter did not register voltages having a magnitude of less than two volts and because, in the case of complicated waveshapes, it was not always possible to determine which oscillations were being counted.

The equipment is shown in Figure 7.

List of equipment:

Dual Beam Cathode Ray Oscillograph, Dumont Type 322-A

Frequency Counter, Hewlett-Packard Model 524A

Oscillograph-Record Camera, Dumont Type 295

Test Oscillator, Hewlett-Packard Model 650A

Voltmeter, Weston Electrical Instrument C.

Ammeter, Weston Electrical Instrument Co.

Photoreader

4. Optical System and Multiplier Phototube

Light from a point in the positive column was reflected from two mirrors (mounted on an optical carriage which in turn was mounted on a rack and pinion arrangement) through a lens and from the lens either directly to a multiplier phototube or, when it was desired to observe a particular spectral line, through a spectrometer to the multiplier phototube. The output of the multiplier phototube was impressed across a 4.7 megohm resistance at the A input terminals of the dual beam oscilloscope.

The point in the positive column under observation was determined by the position of the optical carriage. The condensing lens focused light on the entrance slit of the glass prism spectrometer by means of which a spectral line between 3950 A^{o} and 8200 A^{o} could be selected. Light from the exit slit of the spectrometer fell on the 1P21 multiplier phototube which was surrounded by solid carbon dioxide in a light-tight container of styrofoam. The purpose of this arrangement was to increase the signal-to-noise ratio of the tube by decreasing its temperature.

The dial of the spectrometer was calibrated by comparison with spectral lines from mercury vapor and argon glow.

The sensitivity curve (sensitivity vs. wavelength) of the entire optical system shown in Figure 8 was obtained by the use of a tungsten filament lamp source and the energy-wave length curve of tungsten at 2870 ^{o}K. It shows the magnitude of the light intensity indication on the oscilloscope as compared to the light intensity entering the spectrometer. The 1P21 multiplier phototube used was unusual in that it had a sensitivity curve somewhat different from the manufacturer's curve so that the system used in the experiment was sensitive between 4000 A^{o} and 7600 A^{o}.

The equipment described above can be seen in Figure 9.

List of equipment:

Precision Wave Length Spectrometer, Gaertner Model L 23

Multiplier Phototube, RCA 1P21

Two mirrors, Condensing lens.

5. Oscillograph Display and Analysis

Data was obtained either by visual observations of the oscillogram, the meters, and the frequency counter, or by photographing the oscillogram and recording instrument readings for the mode being considered. Tube voltage was always applied to the B input of the oscillograph. That trace was displayed as the upper waveform of the oscillogram (voltage increasing upward). Light intensity was applied to the A input, the A trace being displayed as the lower sweep on the oscillogram (intensity increasing downward). As mentioned previously, zero reference lines were obtained on photographs by a double exposure technique, one exposure being taken with the vertical amplifiers off and the other being taken with the vertical amplifiers on. Figure 11 is an example of the resulting display.

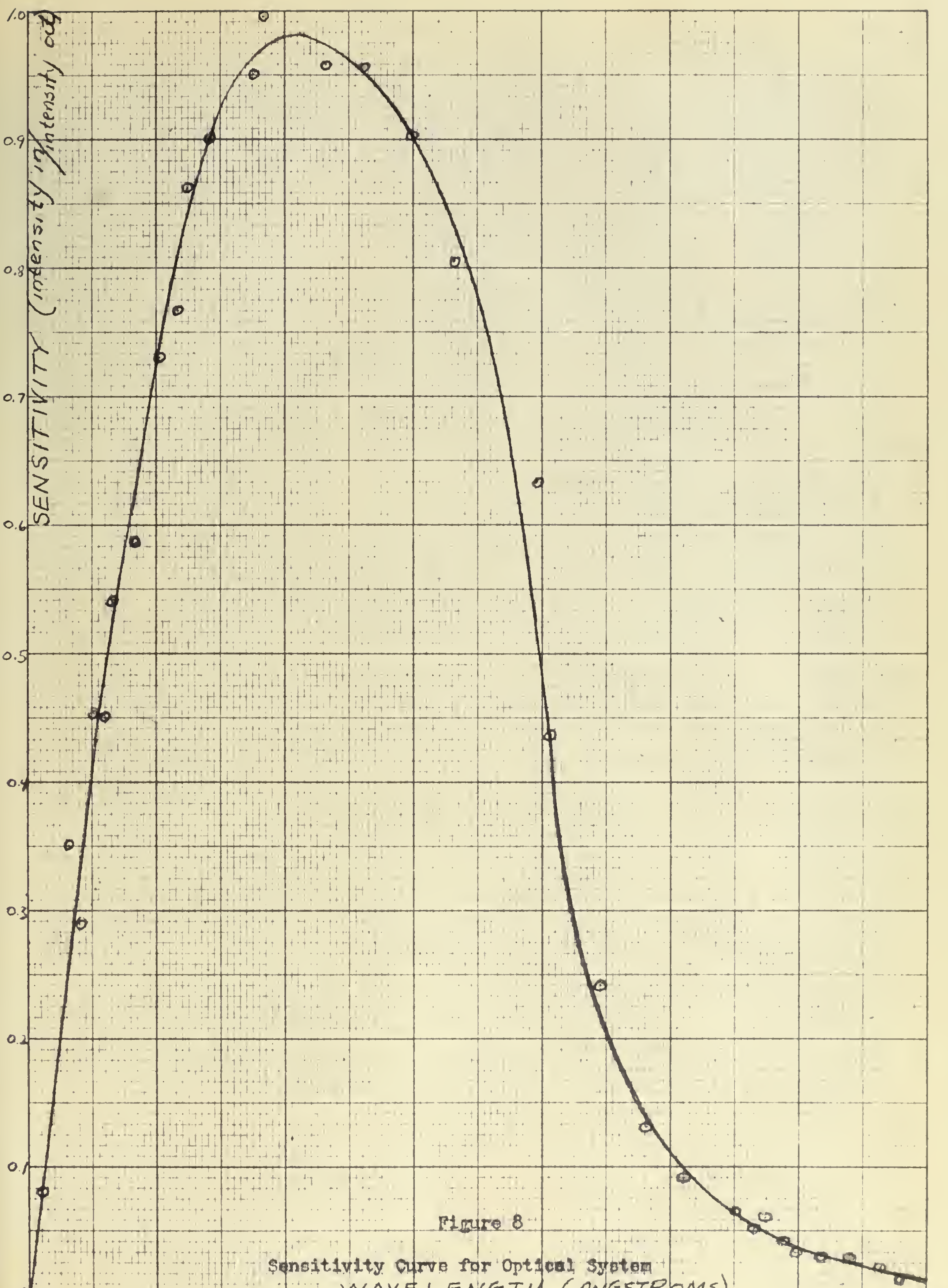


Figure 8

Sensitivity Curve for Optical System

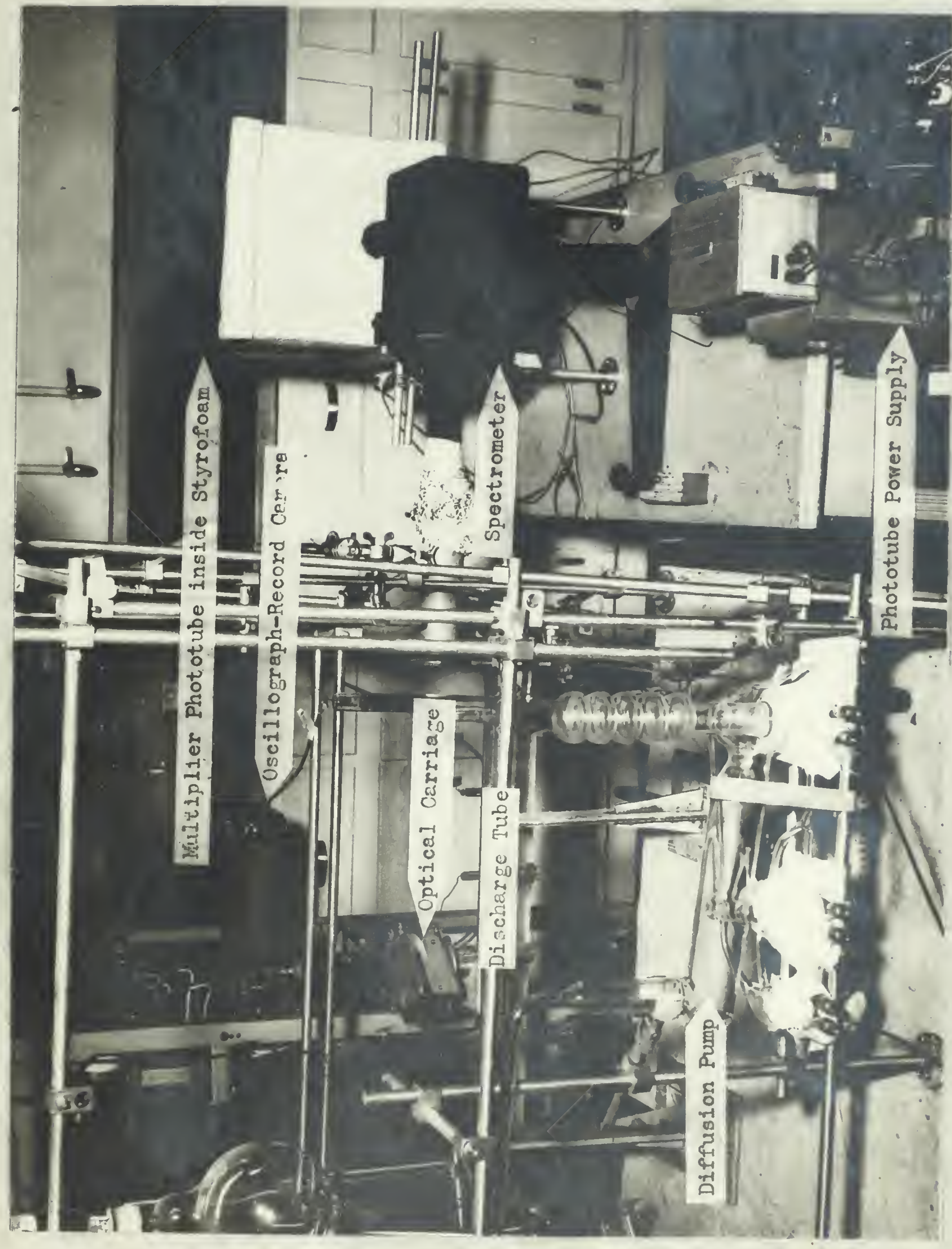


Figure 9

View of Euipment (Close-up)

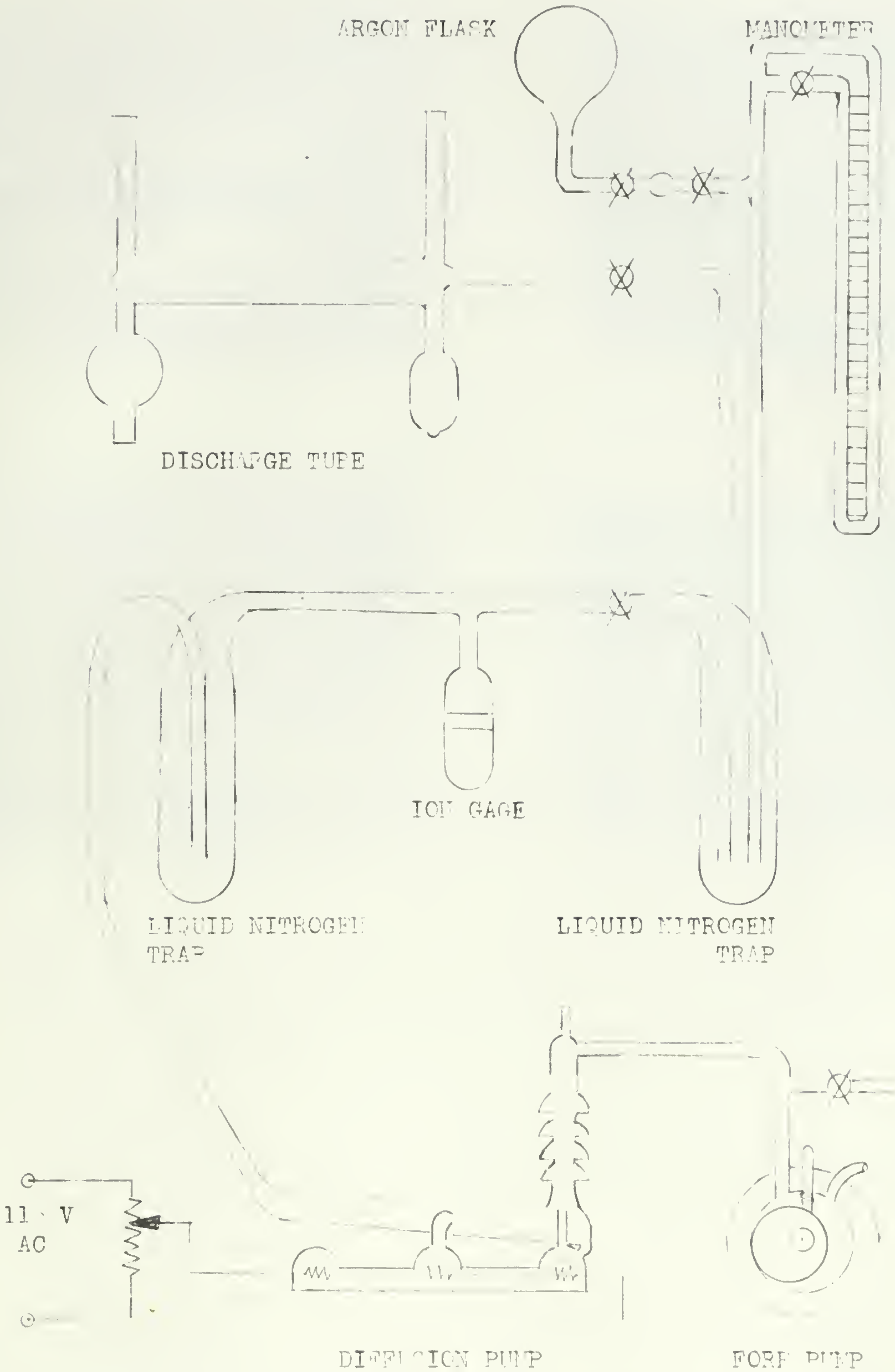
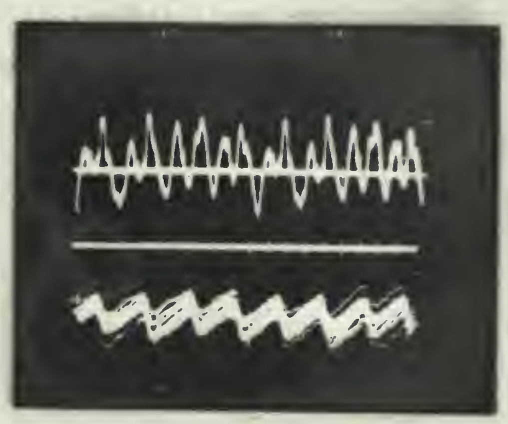


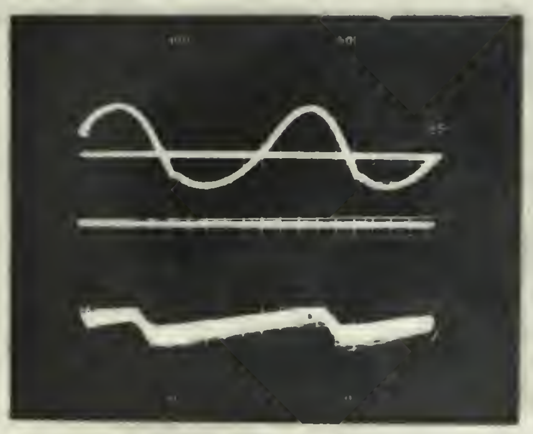
Figure 10

Schematic Diagram of Vacuum System

A



B



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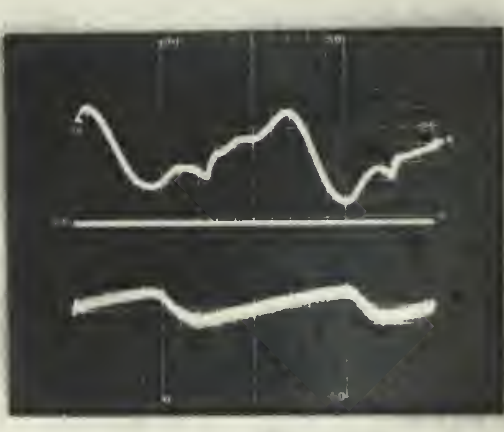


D

Figure 11. Photo-recordings
Upper trace is tube voltage, increasing upward.
Lower trace is light intensity, increasing downward.
Zr cathode; Mo anode.

A. Voltage and light intensity oscillations, unstable.

B. Complex voltage waveform showing 2 complete cycles of voltage. Light intensity oscillations do not have equal amplitudes.

C. Simple voltage waveform.

D. Example of photo-recording of data for motion and intensity curves.
20.5 ma, 300 volts, 9.4 volts amplitude
2330 striations per second. 4198-4200 A°

It was thus possible to measure various quantities of interest. Average tube current was read from an ammeter, and average tube voltage was read from a voltmeter. The amplitude of the voltage oscillations was measured using the oscillograph amplitude calibration arrangement. The waveshape was recorded on the photograph or by pencil sketch. Voltage oscillation frequency was read from the frequency counter. Since there was usually one peak in the light intensity waveform for each major peak in the voltage waveform, the frequency of the light intensity oscillations (frequency of the positive striations) was usually equal to that of the voltage. These two frequencies were verified by displaying a sine wave from the test oscillator on the oscillograph in place of the light intensity.

The steady or DC level of the light intensity waveform represented the light intensity due to the unvarying light emitted from a point in the tube. Maxima of this intensity, then, along the tube represented standing striations. The amplitude of the fluctuations in light intensity represented the instantaneous increase in light intensity due to the passage of a moving striation at the point under observation.

By the use of the precision wavelength spectrometer, these effects were also observed for chosen wavelengths of light.

Since the voltage and light intensity were periodic, it was possible to observe the quantities of interest at various points in the tube as long as the same pattern of events (mode of oscillation) continued.

Since a peak of light intensity represented the passage of a striation at a point in the positive column, it was possible to measure the length of time by which a positive striation followed a particular point in the

voltage waveshape, the length of the sweep being computed from the known frequency of the voltage oscillation. When the optical carriage was moved along the positive column, the light intensity peak was displaced with reference to a voltage peak. Series of photographs were taken in this manner, moving the optical carriage two mm in the direction of the anode between photographs. A positive striation, therefore, appeared earlier in each succeeding photograph. Figure 11 D is an example of a photograph of the type described here.

The phase difference between light of various wavelengths was determined by taking double exposures, photographing the light intensity curve for a different spectral line each exposure. Figure 22 is an example of this type of photograph. The dial of the spectrometer was turned rapidly from one line to the other between exposures. The voltage waveshape was used as a reference and was photographed on each exposure.

After reading the negatives on the photoreader, which enlarged them ten times, the information was plotted as is shown in Figures 17, 18, and 19. The plots provide a means of analyzing motion and intensity of the striations as a function of position in the positive column as discussed in Section IV.

Other observations were taken by recording and plotting average tube voltage, amplitude of voltage oscillations, and frequency of striations as a function of average tube current as discussed in Section III.

Observations using a rotating disc and a rotating mirror were also made.

6. High Vacuum and Filling System

The discharge tube was mounted horizontally on a portable rack and

table with supports for blackout curtains, optical system, and the high vacuum and filling system. A schematic diagram of the vacuum system is shown in Figure 10. The rack supported the diffusion pump, liquid nitrogen traps, filling flasks, manometer, and ion gauge tube as well as the discharge tube. The forepump was located below the rack. Apiezon Grease N was used on all glass stopcocks.

Professor S. H. Kalmbach accomplished necessary modifications and repairs to the system.

As mentioned previously the attainment of a high vacuum is very important in achieving a high degree of purity of the gas under investigation. Much time was consumed in attaining a vacuum of 5×10^{-8} mm Hg as indicated by the ionization gauge. The liquid nitrogen trap nearest the diffusion pump was filled with liquid nitrogen during evacuation; the other was used during filling.

After the system had been degassed thoroughly, filling was accomplished from a one liter pyrex glass flask of Linde high purity argon gas at about one atmosphere pressure which had been sealed into the system. Filling was through a pair of stopcocks on either side of a small bulb reservoir and a liquid nitrogen trap. Gas pressure in the tube was measured with a 100 cm Octoil-S manometer (one cm equals 0.672 mm Hg). After filling, the tube was isolated by means of its stopcock.

List of equipment:

Diffusion Pump, two stage, air cooled, Consolidated Vacuum Corp.
Type GF-25A

Duo-Seal Vacuum Pump, W. M. Welch Manufacturing Co.

Ionization Gauge, Consolidated Vacuum Corp. Type DPA-38 with VG-1A ion tube

Linde high purity argon gas, one liter pyrex glass flask

Induction Heater, Scientific Electric Co. Model AC-5-LB

7. Power Supplies

Power for the discharge tube was obtained from a Sorensen B-Nobatron Model 1000BB. This unit has a variable output voltage of 200-1000 volts DC with a maximum current rating of 500 ma and a DC output regulation of $\pm$ 0.5%.

A carefully regulated DC power supply was necessary to prevent the introduction of stray oscillations into the discharge tube.

The tube current obtainable was limited by the power supply and the circuit to 80 ma.

Power for the multiplier phototube was obtained from a power supply assembled locally.

The phototube was normally operated at 1300 volts.

All other units utilized 115 volts, 60 cycle supply.

Auxiliary equipment is shown in Figure 6.

III. OBSERVATIONS AND ANALYSIS OF VARIATIONS IN VOLTAGE, LIGHT INTENSITY, AND CURRENT

1. General

The variations in discharge tube voltage and light intensity, and the average tube current were observed for the eleven possible combinations of anode and cathode using the methods of Section II.5. Average tube voltage, voltage amplitude, and frequency of light intensity oscillations were plotted against average tube current for each electrode combination to determine characteristic curves. Figures 12, 13, 14, and 15 are examples of curves of this type.

A mode of oscillation can be defined as a particular combination of voltage and light characteristics occurring over a limited range such that there is a periodic pattern longitudinally among the particles in the positive column. This condition was indicated by the appearance of a characteristic oscillogram and, in all cases at two mm Hg pressure, by stationary or standing striations clearly visible throughout the positive column. A particular mode may be stable such that its characteristics will not change for periods of hours, or it may be unstable such that oscillations as shown in Figure 11A will commence after only a few seconds. Generally a mode could be repeated at will by adjusting tube current.

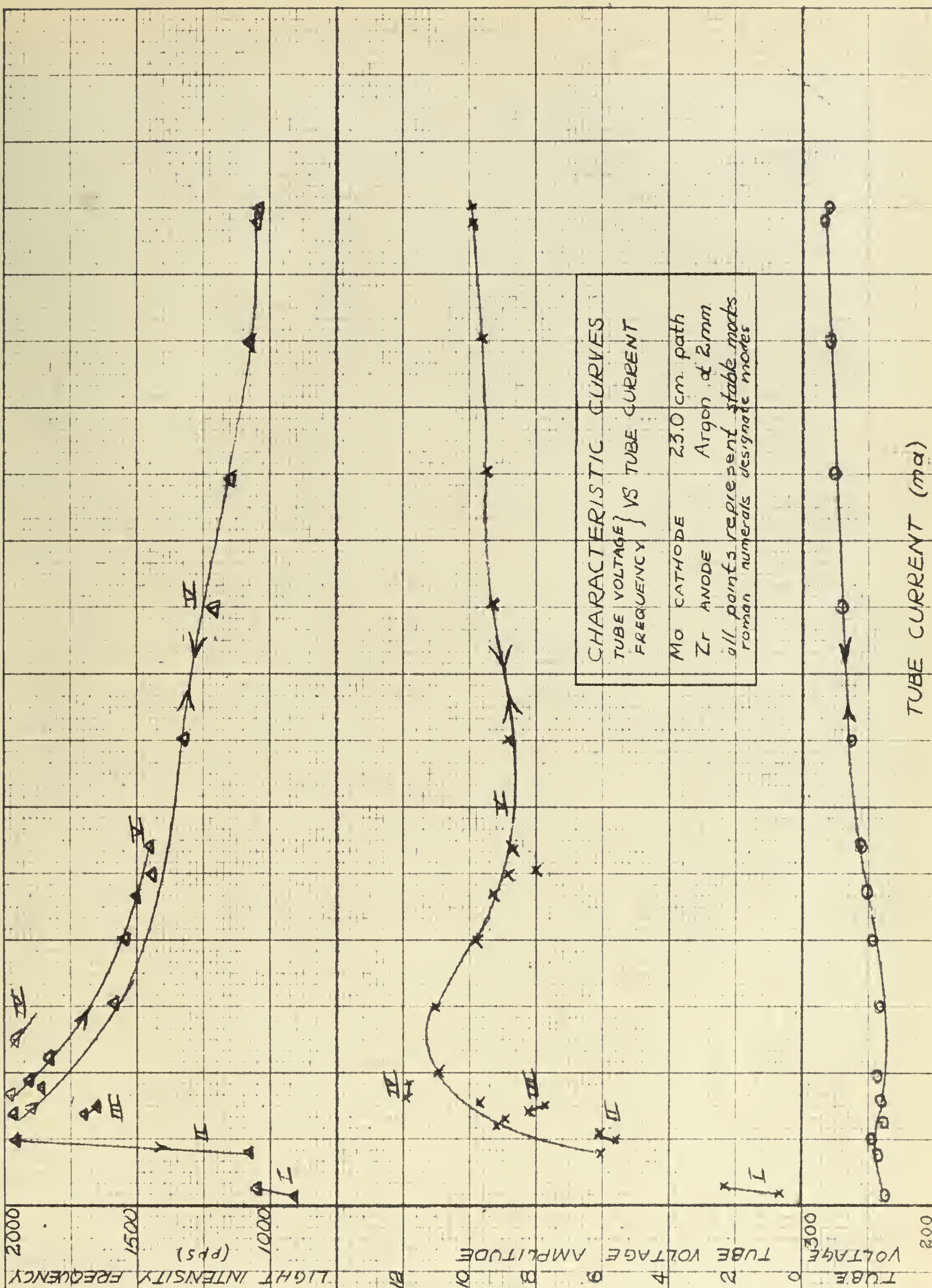
It has been noted previously (4, 5, 13, 14) that there is a definite hysteresis effect evidenced by different values of tube voltage at the same current depending upon whether the particular current was reached by increasing or decreasing the current. The direction of current change is indicated on the curves by arrows. Plots of individual modes which have similar characteristics may be related by smooth curves.

It was not possible to predict the current at which a mode would occur, and modes often occurred with very different characteristics even though the change in current was small. From a comparison of the 11 curves plotted, the cathode material and the form of the discharge path (short vertical path, or longer vertical and horizontal path as shown in Figure 4) were found to have a marked effect on the behavior of the discharge. Figure 16 is a tabular summary of the occurrence of stable modes in argon glow. In each case the cathode was examined in conjunction with the three other electrodes as anode.

Generally only stable modes were plotted. Although the plots of modes varied widely, there was a tendency to follow a general pattern. Modes were more stable and more numerous at the lower currents. The voltage-current characteristic curve in some cases had a definite hysteresis loop; in other cases there was none. Figure 12 is an example of the general pattern, the voltage curve having no hysteresis effect. Figure 13 for a different cathode and anode combination shows less rigid conformity to the general pattern, but there is a definite hysteresis effect. Figure 14 is an example of the effect of changing from a short vertical discharge path to a longer vertical and horizontal path while using the same cathode and anode materials as in Figure 13.

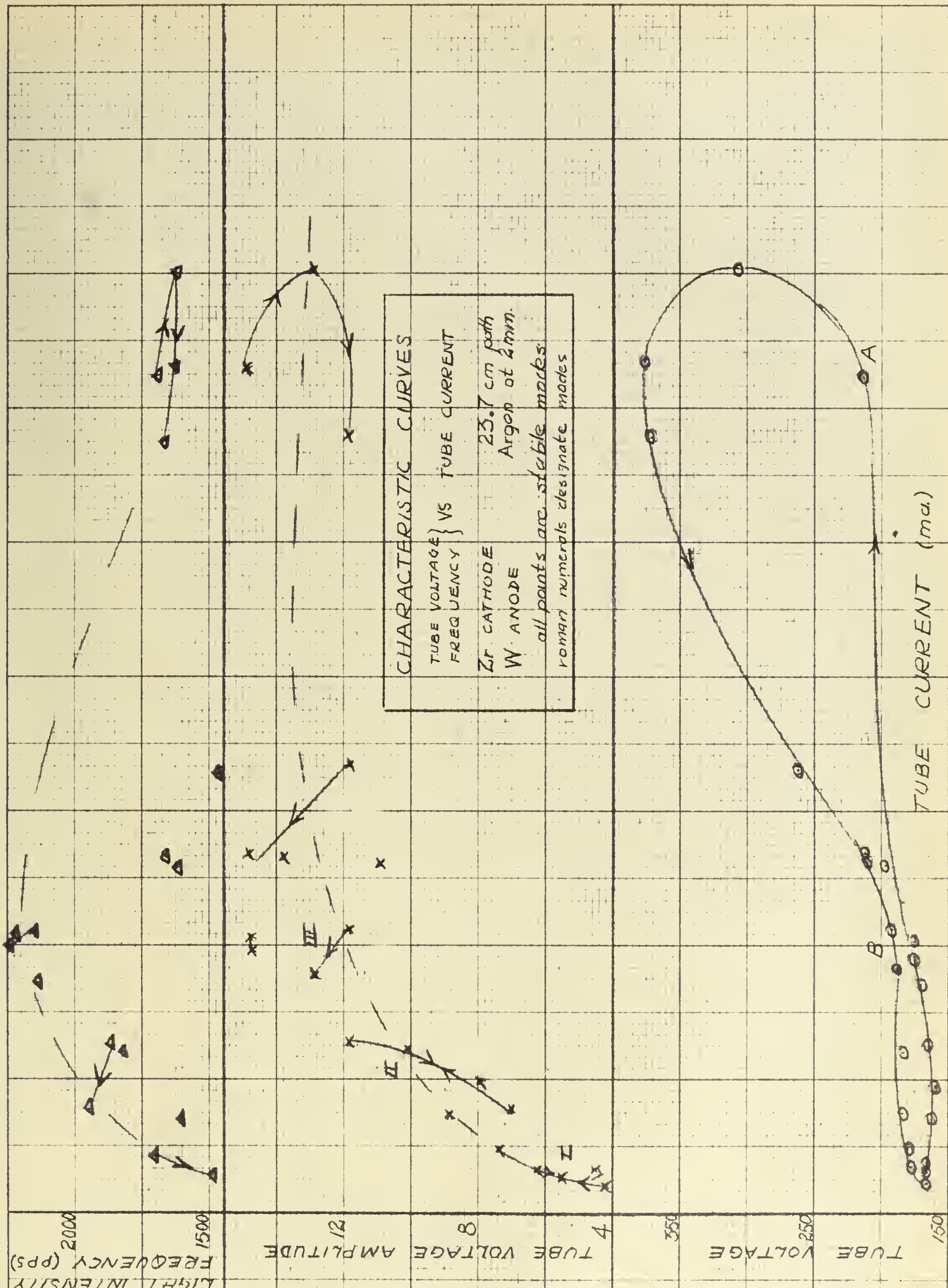
The general shape of the characteristic curves is similar to that found by Donahue and Dieke (4) at 2.1 mm Hg. However, there are more modes in Figure 12. The shape varies greatly with pressure as shown in Figure 15 for 12 mm Hg.

Except for a short distance near the cathode, the positive column usually filled the entire length of the tube. In some cases the positive



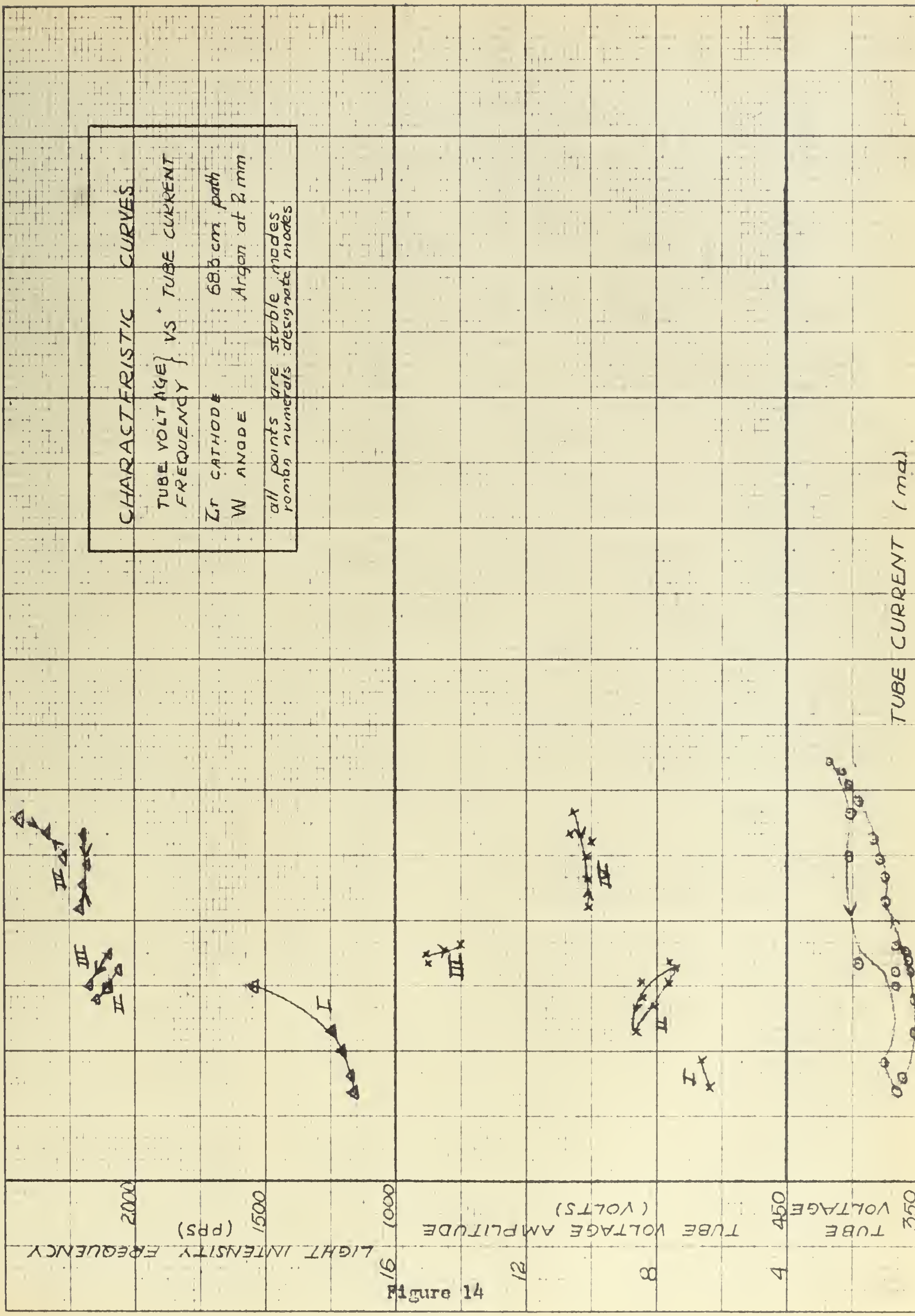
CHARACTERISTIC CURVES
TUBE VOLTAGE
FREQUENCY
VS TUBE CURRENT
Mo CATHODE 23.0 cm. path
Zr ANODE Argon at 2mm.
all points represent stable modes
roman numerals designate modes
TUBE CURRENT (ma)
LIGHT INTENSITY FREQUENCY
(pps)
TUBE VOLTAGE AMPLITUDE
TUBE VOLTAGE

Figure 12



CHARACTERISTIC CURVES
TUBE VOLTAGE
FREQUENCY
VS TUBE CURRENT
Zr CATHODE
W ANODE
23.7 cm path
Argon at 2mm.
all points are stable modes
roman numerals designate modes
TUBE CURRENT (ma.)
TUBE VOLTAGE
TUBE VOLTAGE AMPLITUDE
LIGHT INTENSITY FREQUENCY (pps)
A
B
I
II
III
0
10
20
30
40
50
60
70
150
250
350
4
8
12
1500
2000

Figure 13



CHARACTERISTIC CURVES
TUBE VOLTAGE } VS TUBE CURRENT
FREQUENCY
Zr CATHODE 68.5 cm path
W ANODE Argon at 2 mm
all points are stable modes
roman numerals designate modes
TUBE CURRENT (ma)
0
10
20
30
40
50
60
TUBE VOLTAGE
350
450
TUBE VOLTAGE AMPLITUDE (VOLTS)
4
8
12
16
LIGHT INTENSITY FREQUENCY (PPS)
1000
1500
2000
I
II
III

Figure 14

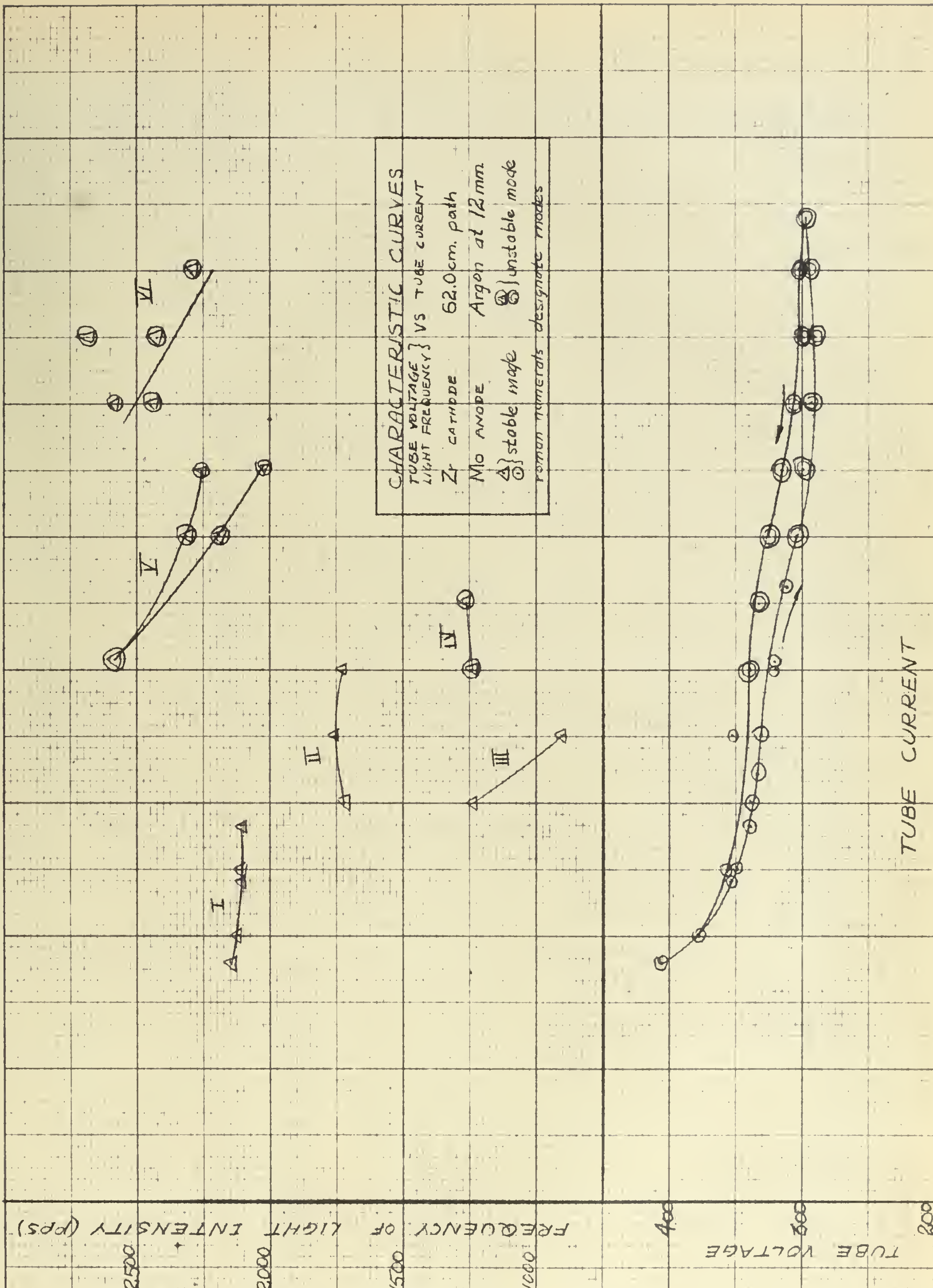

CHARACTERISTIC CURVES
TUBE VOLTAGE } VS TUBE CURRENT
LIGHT FREQUENCY }
Zr CATHODE 62.0cm. path
Mo ANODE Argon at 12mm.
stable mode
unstable mode
roman numerals designate modes
I
II
III
IV
V
VI
TUBE CURRENT
FREQUENCY OF LIGHT INTENSITY (pps)
TUBE VOLTAGE

Figure 15

SUMMARY OF OCCURRENCE OF STABLE MODES
Argon, 2 mm Hg Pressure

	Zr Cathode (4.75 sq cm)		Mo Cathode (65 sq cm)		W Cathode (10 mil wire)	
	Short Discharge Path	Long Discharge Path	Short Discharge	Long Discharge	Short Discharge	Long Discharge
Conformance to General Pattern	Voltage conforms Amplitude and freq. conform generally	Voltage conforms Amplitude and freq. do not conform	Conform	Conform generally	Conform generally	Voltage and freq. conform Amplitude does not conform
Hysteresis (Max. voltage difference)	170 V at 60 ma	80 V at 40 ma	0 V	1 V	8 V at 28 ma	1 V
Range of voltage amplitudes	4–15 V	3–24V	1–11 V	15–21 V	1–20 V	3–10 V
Range of striation frequencies	1100–5200 sec^{-1}	2400–11,400 sec^{-1}	1–2200 sec^{-1}	1100–1800 sec^{-1}	700–2400 sec^{-1}	1900–2700 sec^{-1}
Range of current for stable modes	2–70 ma	8–35 ma	1–75 ma	7–10 ma 66–71 ma	2–49 ma	7–17 ma
Distance from cathode to head of positive column	2.2–3.2 cm	2.2–3.0 cm	0–2.6 cm	0–2.6 cm	—	—
Stability (In general, modes were more stable at currents below 35 ma)	Modes generally unstable and few in number above 35 ma		Stable modes throughout above current range; most between 2–10 ma.	Very few stable modes. Only two stable modes in each current range above.	Stable modes throughout above current range, most between 2–8 ma.	Stable modes in above range.

Figure 16

column appeared to extend to the cathode. It was not possible to detect regions of the glow other than the positive column and the dark space near the cathode. The length of this dark space varied with current. The pink-purple color of the glow became more nearly blue at higher tube currents. A ball of light formed near the cathode at intermediate currents (approximately 30-60 ma) blending into the positive column at higher currents.

2. Observations and Analysis

a. Effect of cathode material

The mode (tube voltage, frequency, and amplitude vs current) curves were similar for combinations of electrodes having the same cathode material. The anode material had little effect. A similar observation was made under different circumstances. Those circumstances and a further discussion are included in Section IV.

The use of a molybdenum cathode resulted in some distinctive phenomena. The molybdenum cathode consisted of sheets of the metal constructed of four fins placed at right angles to each other so that the area of the electrode was large (approximately 65 square centimeters) as compared to the zirconium electrodes (approximately 4.75 square centimeters) and the tungsten wire. When the molybdenum electrode was used as cathode, and the 23.0 cm path was observed, the most regular set of curves resulted, and modes were stable over the entire range of current. There was very little hysteresis. When a 62.0 cm discharge path was used with the molybdenum cathode, only four modes were observed (two at low currents and two at high currents) regardless of whether zirconium or tungsten was used as the anode material.

Another observation which may be associated with the above effects was that, when the molybdenum cathode was being used, the positive column appeared to commence at the cathode at low currents although the light was not intense at these currents. The distance from cathode to the head of the positive column then increased with increasing current until it was 2.6 cm at 70 ma. Using a zirconium cathode, the positive column did not appear to reach to the cathode. The distance varied from 2.2 cm. at low currents to 3.0 cm at 60 ma. These effects were independent of anode. At a pressure of 12 mm (zirconium cathode) the positive column appeared to reach to the cathode at all currents.

b. Hysteresis

There was a definite hysteresis effect for most electrode combinations, more pronounced for tube voltage than for voltage frequency or for voltage amplitude. The tube voltage was generally less for increasing than for decreasing currents. That is, very similar modes appeared at the same current for increasing or decreasing currents but at different tube voltages. Readings plotted were taken after all meter readings appeared to have reached a constant value. Figure 13 is an example of the type of hysteresis curve found. It is similar to that of Donahue and Dieke (4).

There was little if any hysteresis effect at low currents. The effect was a maximum at the higher currents obtainable with any electrode combination.

Hysteresis has been briefly noted previously (3, 4, 7, 9, 13, 14) and has been explained (3) as ionization "inertia." That is, with increasing current, there is a lag in the production of additional ionization and, with decreasing current, there is a lag in deionization

(corresponding to a lower tube voltage); that is current lags voltage. Our phenomena appear to differ from this inertia effect in that the tube current followed a change in the applied voltage almost immediately, but tube voltage lagged by a matter of minutes. The voltage lag was less for increasing current than for decreasing current.

This effect might well be a "turbulence" phenomenon. The electron flow (current) may be initially a "laminar" flow and increase rapidly with increasing voltage up to a certain point (A, Figure 13). At this point "turbulence" occurs, and after this point an increase in tube current corresponds to a much greater increase in tube voltage. We noted that soon after the "turbulent" regime was established, a slight increase in applied voltage resulted in a very sharp increase in turbulence, and a correspondingly large increase in tube voltage. Subsequently it appeared that tube voltage and current decrease together in the turbulent regime until at another point (B, Figure 13) laminar flow of the electrons is again established.

In line with this tentative hypothesis, it was observed that the hysteresis effect was more pronounced at higher voltages and was more apparent during rapid current changes. With a rapid increase in applied voltage the tube current responded quickly, then a turbulence seemed to develop, the tube voltage rose and current dropped slowly until a point of equilibrium was reached (4).

At higher current unstable modes could be obtained with a decreasing current that could not be obtained with an increasing current.

c. Diffusion and Turbulence

The short, direct discharge paths resulted in the most complete and regular characteristic curves. Longer, indirect paths resulted either in

numerous unstable and complicated modes which were scattered from the general pattern or in the failure of these modes to appear at all such that no mode or only a few modes appeared. Modes which occurred at higher currents for a short path did not appear for a long path. The current range of stable modes for long paths was approximately one-half of that for the short paths. Hysteresis appeared to be somewhat less for the long paths.

Diffusion of ions and electrons to the walls of a tube is known to have a strong effect on the maintenance of a discharge and on the conditions existing in the discharge (3, 15). The opportunity for diffusion was obviously much greater when the longer, vertical-horizontal path was used than when the shorter, vertical only path was used. The positive column, which in straight portions of the tube, was concentrated along the axis of the tube appeared to touch the tube wall at both right angle bends in the tube and at the three probes spaced along the positive column. Thus, the portion of the positive column in which the concentration of positive ions and electrons was greatest was in direct contact with the walls in two locations and at the probes greatly increasing the opportunity for diffusion to the walls.

The discharge tube was fabricated with three cylinder and two wall probes projecting into the region of the positive column. The probes appeared to have a strong effect in disturbing the patterns in the positive column even without any voltage being applied to them.

The effect of placing a magnet near the positive column seemed to be similar to that of increasing the length of the discharge or of increasing the current. Corresponding modes occurred when the magnet was in place and when it was removed, but each occurred at a lower current

with the magnet in place. It was seen that the glow was displaced radially and became more narrow and concentrated at the magnet and in the region 1.0 to 1.5 cm to the anode side of the magnet than in the rest of the column.

With no magnet in place as current was increased, the diameter of the positive column decreased so that it appeared not to extend to the walls of the tube.

Because of the irregularities caused by wall and probe conditions, it may be difficult to compare results obtained using this tube with results obtained using other tubes.

d. Effect of Tube Pressure

Observations were also taken at a pressure of 12 mm Hg of argon using a zirconium cathode and a molybdenum anode and a 62.0 cm path in order to compare results using the tube to those of other investigators (4, 5, 13, 14) who worked at 12 mm Hg pressure using tubes of a different shape. The greater tube pressure resulted in fewer and more stable modes and very different characteristics from those obtained at 2 mm Hg. As shown in Figure 15 the resulting curves compared favorably with those obtained by others (4, 5, 13, 14) in that the voltage curve was generally hyperbolic, and the frequency curves generally paralleled the voltage curve. No standing or stationary striations were observed at this pressure.

As noted previously, at the greater tube pressure the positive column appeared to reach to the cathode (zirconium).

Since the mechanisms in the tube are largely dependent upon particle interactions, it might be expected that the phenomena would vary greatly with density.

e. Relation of Positive Striations to Voltage Maxima

Donahue and Dieke state (4, 7) that there is a voltage maximum each time a positive striation leaves the region of the anode, and a voltage minimum occurs each time a negative striation leaves the cathode. Due to our tube arrangement, this phase relation could not be observed, but it was noted in general that during a voltage cycle the number of positive striations and the number of most "prominent" voltage maxima were equal. All prominent voltage peaks were not of the same amplitude, and there were usually a number of subsidiary voltage peaks with different amplitudes. Generally the amplitude of the variations in light intensity were equal, but a few cases were observed in which they were unequal.

The most complicated voltage waveforms had many positive striations appearing during one complete voltage cycle. Modes falling on the same characteristic curve usually had an equal number of positive striations during each complete voltage cycle except that those having either one or two positive striations per voltage cycle might be on the same mode curve. The modes having the more complicated voltage waveshapes generally were farthest from the general pattern of the characteristic curves. Figures 11B and C are examples respectively of a rather complicated and a rather simple waveshape.

Since there is apparently some relation between the frequency of the positive striations and the voltage oscillations and since the striations may establish the sequence of events within the tube, the amplitude and frequency of the positive striations may be considered to be the distinguishing characteristics of the mode.

Kolkhorst and Strong (14) have noted that a complete recurrent voltage

wave may include several prominent voltage peaks such as shown in Figure 11B. The voltage wave frequency they refer to as the phase frequency (cps) and the frequency of the prominent voltage peaks they call the pulse frequency (pps). We agree with Kolkhorst and Strong that there is a close correlation between striation frequency and pulse frequency, and only a secondary correlation with phase frequency depending on the number of "pulses" per phase or voltage cycle. Generally there was a one to one relation between pulse and striation frequency, most of the wave shapes studied being relatively simple. However, occasionally the wave shapes were complicated as shown in Figure 11B and the "prominent" voltage peaks which generally corresponded to striations could not be differentiated by eye from subsidiary peaks which did not seem to have corresponding striations. In such cases the frequency counter, which was set to monitor voltage frequency, was not a reliable indication of the striation frequency. A trace from the test oscillator was caused to coincide in phase with the striation trace on the dual beam oscilloscope face. The striation frequency was thus determined directly. As can be deduced from the foregoing, there was no completely consistent one to one correlation between striation frequency and either pulse of phase frequency. However, as previously remarked, in most cases where only simple wave shapes were involved and there was no question as to how many pulses existed per cycle, there was a one to one relationship between striation frequency and pulse frequency.


INTENSITY arbitrary units
15
20
25
30
ANOMALY IN INTENSITY DUE TO MAGNET
Zr.-CATHODE
⊙ 6950 Å
× 4200 Å
△ ALL λ's
Mo.-ANODE
⊡ MAGNET
ALL λ's
13.4 ma.
325 V
300 V
20.5 ma
2330 pps
9.4 v p-p
TIME AFTER VOLTAGE MAXIMUM (micro-sec.)
0
100
200
300
400
500
600
700
800
MAGNET
ANOMALY IN CURVE DUE TO MAGNET
CENTER PROBE
RIGHT PROBE
I
II
II
I
DISTANCE FROM CATHODE (cm.)
28.0
29.0
30.0
31.0
32.0
33.0
34.0
35.0
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0

Figure 17

IV. OBSERVATIONS AND ANALYSIS OF LIGHT INTENSITY AND MOTION OF STRIATIONS IN THE POSITIVE COLUMN

1. General

For most stable modes at a pressure of 2 mm of argon, very pronounced standing or stationary striations were visible at more or less regular distances throughout the positive column. This was true for all electrode combinations and for either the long or the short discharge paths. The effect was evident but less pronounced as the intensity of the glow became brighter with increasing current. These standing striations remained fixed while the moving striations moved through the tube. At a pressure of 12 mm the standing striations could not be seen although the moving striations were observed.

The movement of moving striations through stationary ones was most directly evident when the positive column was viewed through a rotating disc having notches cut from the circumference. However, other data lead to interpretation which agreed with these observations.

Donahue and Dieke mention their observation that the positive column is striated when diatomic gases are used (6). They also state that in a few cases faint but definite stationary striations could be seen toward the cathode end of the positive column when argon at 12 mm was examined (4). They note that in diatomic gases standing striations can be observed which have moving striations passing through them (6).

The standing striations reported here resembled those described above for diatomic gases. They extended throughout the positive column and were traversed by moving striations. References to standing striations hereafter will concern this unusual case.

Evidences of negative striations have been noted by several investigators (6, 7, 10, 13, 17, 21). Negative striations were not observed during this study. However observations were limited to the relatively bright glow of the positive column, so it was not particularly surprising that they were not observed.

The motion of positive striations and the variation in light intensity were observed in the positive column using the methods of Section II.5. The time of the passage of the positive striations after a voltage maximum and the variations in light intensity from standing striations and from moving striations were plotted as a function of position in the positive column. This was done for various electrode combinations (zirconium cathode, molybdenum anode; zirconium cathode, zirconium anode; tungsten cathode, molybdenum anode) so that the effect of a change in cathode using the same anode could be compared with the effect of a change in anode using the same cathode, and in order to study striation motion and effects. Data was taken for each of these three electrode combinations using light of two different wavelengths (the 4198–4200 A^{o} doublet and a pair of lines at 6937–6965 A^{o}). Velocity changes were not as well defined in the case of the zirconium cathode and anode as in the other cases. Several such studies were also made using all wavelengths within the sensitivity range of the multiplier phototube (spectrometer not in place). Other data were taken with a permanent magnet placed 1.5 cm to the right of the center probe.

Information concerning atomic transitions and excitation voltages for the spectral lines observed (14, 2, 16) is included in Figure 20.

After plotting the information obtained from series of photographs

obtained using the parameters described above, it was possible to analyze the motion of the positive striations through the positive column and the corresponding variations of light intensity as well. Figures 17, 18, and 19 are examples of these curves. Comparisons of the curves were made by physically superimposing all possible permutations of motion and intensity curves. In all cases, curves representing the same cathode were found to have the same shape although they might differ in phase, in average slope and/or in amplitude. That is, the inflection points, maxima, minima, and relative amplitudes corresponded exactly in sequence (within experimental accuracy) although compressed or expanded with regard to distance along the tube. It was noted that differences in tube current, wavelength of light observed, and even use of magnet did not change the fundamental shape of the curve. In the cases of differing cathode but same anode, there was no such similarity. It did not appear that changes in shape occurred at any particular distance from the head of the positive column.

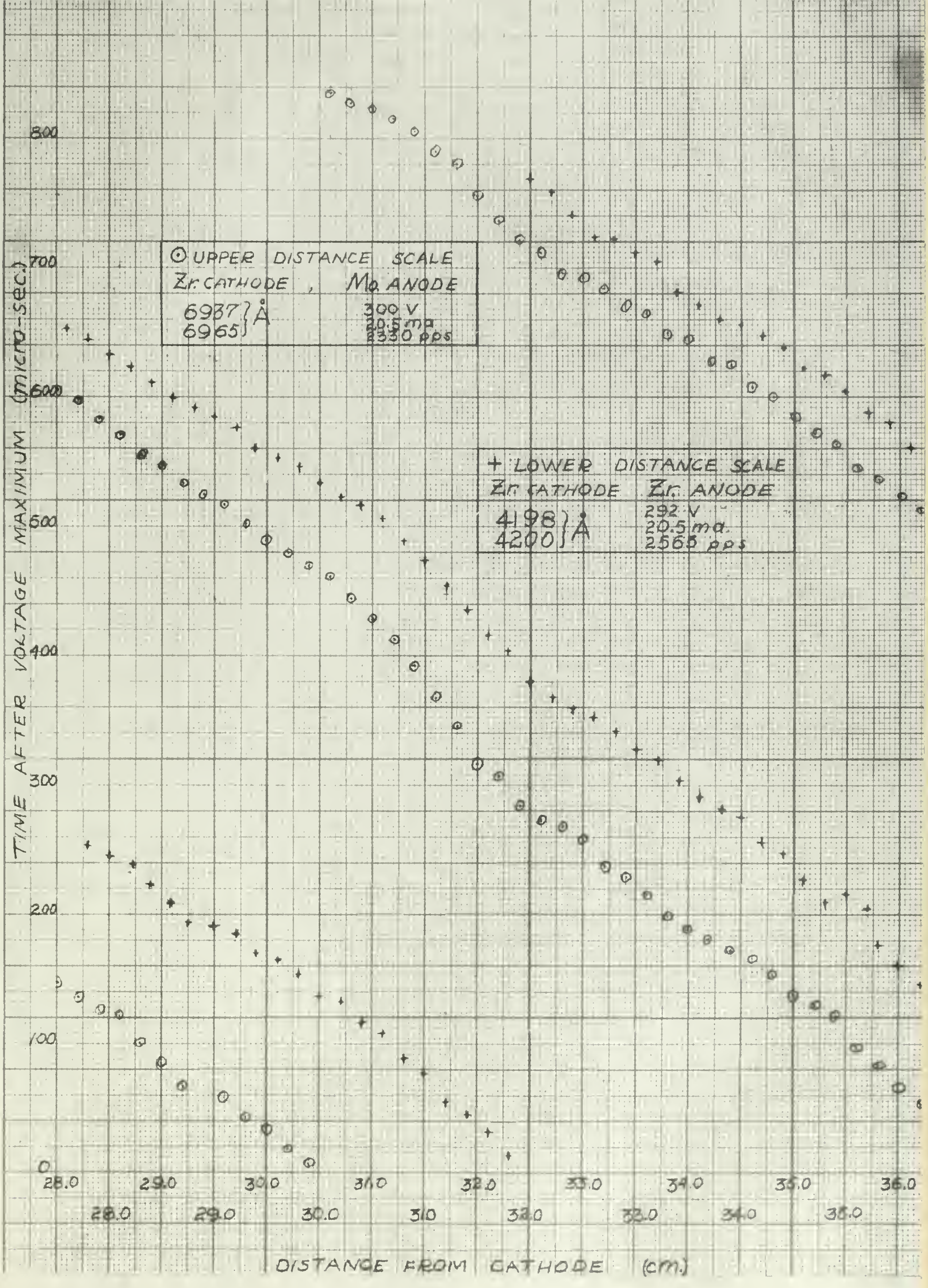
In all cases two positive striations, indicated as striation I and striation II in Figure 17, were followed through approximately 20 cm of the positive column, and the variations in both the standing and the moving striations were observed as shown in Figure 19.

Figure 21 is a summary of the analyses made of these curves.

2. Observations and Analysis

a. Effect of Cathode Material

The cathode used determined the motion of the positive striations while the anode material seemed to have no effect. This agrees with the observations noted in Section III.2.a. There was some tendency for all positive striations observed to follow a similar motion for at least



⊙ UPPER DISTANCE SCALE
Zr. CATHODE , Mo. ANODE
6937 Å
6965
300 V
20.5 ma
2330 pps
+ LOWER DISTANCE SCALE
Zr. CATHODE Zr. ANODE
4198 Å
4200
292 V
20.5 ma.
2565 pps
TIME AFTER VOLTAGE MAXIMUM (micro-sec.)
DISTANCE FROM CATHODE (cm.)
0
100
200
300
400
500
600
700
800
28.0
29.0
30.0
31.0
32.0
33.0
34.0
35.0
36.0

Figure 18

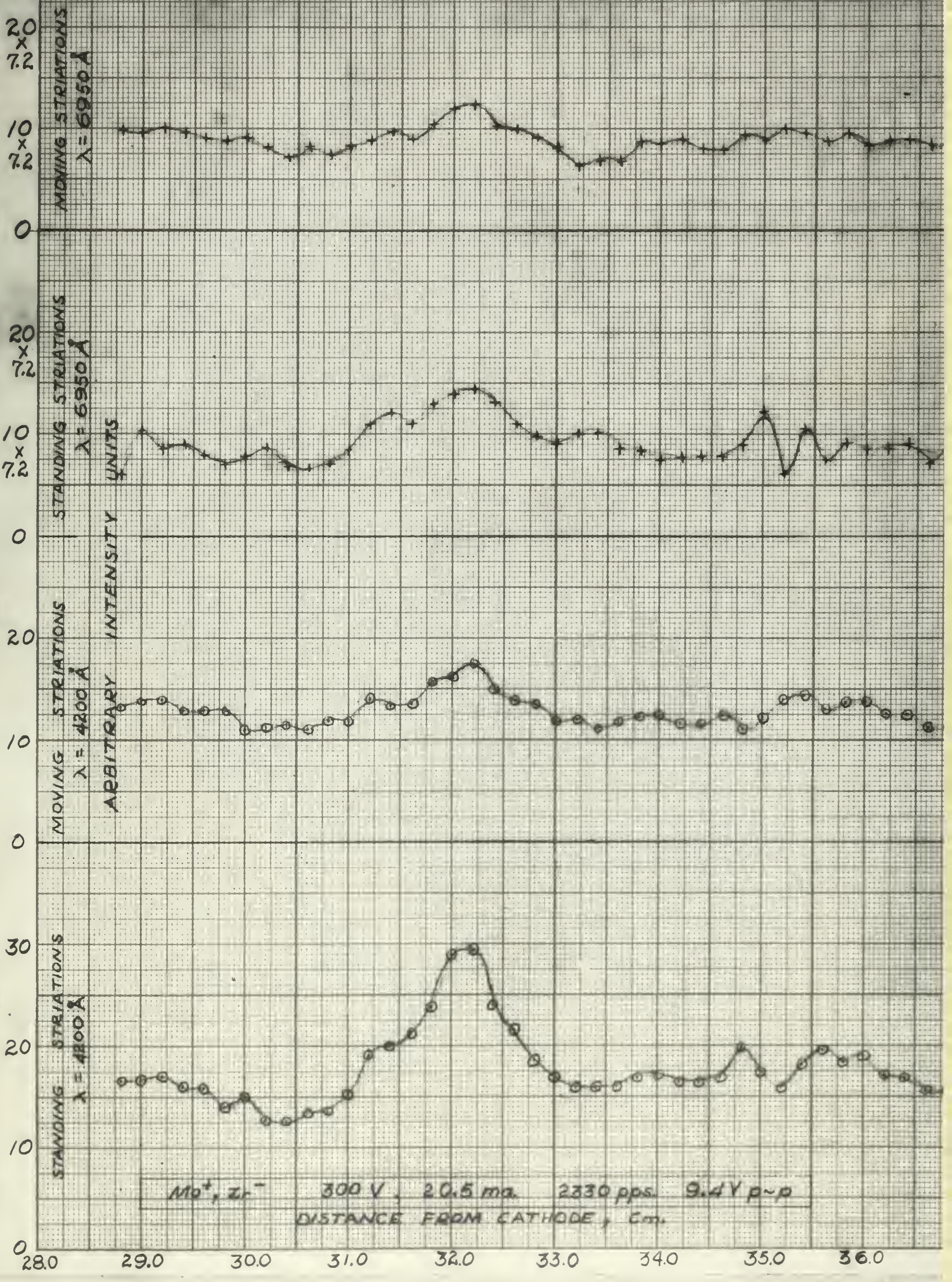

MOVING STRIATIONS
λ = 6950 Å
STANDING STRIATIONS
λ = 6950 Å
MOVING STRIATIONS
λ = 4200 Å
STANDING STRIATIONS
λ = 4200 Å
ARBITRARY INTENSITY UNITS
20 × 7.2
10 × 7.2
0
30
20
10
Mo+, Zr−   300 V, 20.5 ma.   2330 pps.   9.4 V p~p
DISTANCE FROM CATHODE, Cm.
28.0
29.0
30.0
31.0
32.0
33.0
34.0
35.0
36.0

Figure 19

SPECTRAL LINES OF ARGON

Line	Wavelength in Air Angstroms	Atomic Transition	Excitation Voltage
1.	4158.59	5P6—4S5	14.53
	4164.18	5P7—4S5	14.52
2.	4198.32	5P5—4S4	14.50
	4200.67	5P9—4S4	14.52
3.	4272.17	5P7—4S4	14.52
4.	4300.10	5P8—4S4	14.50
5.	4333.56	5P3—4S4	14.69
	4335.34	5P2—4S4	14.68
6.	6965.43	4P2—4S5	13.33
7.	7067.22	4P3—4S5	13.30
8.	7383.98	4P3—4S4	13.30
9.	7503.87	4P1—4S2	13.48
10.	7635.10	4P6—4S5	13.17

Figure 20

SUMMARY OF POSITION- TIME AND INTENSITY CURVES

	Zr Cathode Mo Anode 2 mm Hg 13.2 ma unless otherwise indicated	20.5 ma	12 mm Hg 30 ma & 60 ma	Zr Cathode Zr Anode (Anode changed; cathode not changed) 2 mm Hg 20.5 ma		W Cathode Mo Anode (Cathode changed; anode not changed) 2 mm Hg 11.2 ma unless otherwise indicated
Distance between standing striations, d	3.0 cm 3.3 (13.4 ma) 3.4 (9 ma) 2.0 (16 ma) 2.2 (23 ma)	3.3 cm	No standing striations	3.0 cm		2.7 cm 2.5 (14 ma)
Positive striation wavelength	6.3 cm 3.4 (9 ma) 2.0 (16 ma) 4.4 (23 ma)	6.7 cm	5.5 cm	6.9 cm		5.7 cm 2.5 cm (14 ma)
Velocity Average Maximum Minimum	 140 m/sec 510 60	 155 m/sec 365 100		 175 m/sec 250 90		 140 m/sec 400 40
Max. velocity precedes max. intensity by:	1.5 cm	1.4 cm		0.7–1.2 cm	Velocity changes	0.8–1.0 cm
Min. velocity precedes max. intensity by:	0.4 cm	0.3 cm		0.3 cm	poorly defined	0.0–0.5 cm
Intensity amplitude ratio $\frac{6950\ A^o}{4200\ A^o}$	4.2			6.3		6.2

Figure 21

A B

Figure 22. Photo-recording Showing Phase Differences between Spectral Lines

Upper trace is voltage, increasing upward.
Lower traces are light intensity, increasing downward.
4198-4200 A° (Center)
7503 A° (Bottom)

A. At position of maximum light intensity of standing striation.
23 ma, 275 volts
2166 striations per second

B. At position of minimum light intensity between standing striations.
20 ma, 277 volts
2340 striations per second

short distances. Curves obtained using the same cathode had almost identical motion regardless of anode while curves obtained using the same anode but different cathodes showed quite different motion. Figure 18 shows the manner in which two curves obtained using the same cathode but different anode correspond even though the modes were different. No such comparison was possible using the same anode but different cathode material. When the same cathode material was used, the variations in light intensity were very similar although to a less marked degree than for the motion curves. This can be explained by the fact that intensity data was generally not as accurate as motion data. The effect of cathode on dark space distances is discussed in Section III.2a and is summarized in Figure 16.

Evidently the cathode material and/or the geometry of the cathode have a strong effect on the behavior of the striations and, therefore, on the particles in the tube. These events depend upon the abundance of the electrons, the energy which they acquire in the tube, and the energy from the gas required to produce them, whether they be produced by thermionic emission, field emission, photoelectric emission, or by positive ion or metastable atom bombardment. The emitted electrons appear to be produced for the most part by positive ion bombardment, although photo-emission, thermal emission and field emission may play a greater or smaller part. It has been noted that the low work function surfaces are generally the best emitters when subjected to positive ion bombardment (3). Photo-emission, and thermal emission are inversely proportional to the work function of the material. The Schottky and the Fowler-Nordheim equation for field-emission current density also show that the current

density is an inverse function of the work function (15). The work function is a unique characteristic of the material.

Further, the geometry of the three cathodes was very different. The molybdenum cathode had a large area which provided for emission of more electrons and permitted cooling as compared to the zirconium cathodes. The tungsten cathode was a wire which was observed to become red hot at currents above about 20 ma.

Electrons leaving the surface of the cathode are known to have relatively little energy. They gain energy in the cathode fall and lose energy in the negative glow before passing into the positive column. It seems to be in the negative glow (3,7,22) that the exchanges of energy take place which may help to explain the formation and motion of striations. It seems reasonable, therefore, that the source of electrons should have a strong influence on the behavior of the striations in the discharge.

Pupp has found that for a homogeneous positive column in argon the plasma reacts to anode oscillations (19). This effect is independent of the cathode. The anode drop serves primarily the purpose of producing ions at the anode in quantities sufficient to maintain the plasma near the anode. By studying anode oscillations he determined that the homogeneous plasma is stable at varying distances from the anode (3-10 cm.) depending upon the "degree of stability" (sic). He states, however, that moving striations have nothing to do with the disturbance effect of the anode.

b. Light Intensity and Velocities

A curve of the intensity due to standing striations is plotted at the top of Figure 17 for comparison with the motion curves. Similar curves

for standing striations and for moving striations are plotted in Figure 19 for the two light wavelength combinations(4198, 4200 A^{o}; 6937, 6965 A^{o}). The curves for standing striations represent the unvarying or DC portion of the light intensity on the oscillogram, the standing striations corresponding to the peaks of these curves. The curves for moving striations represent the amplitude of the fluctuating AC component. The steady intensity curves, therefore, represent the steady light due to the non-oscillating portion at each point in the positive column, while the moving striation curves represent the instantaneous value of light intensity due to the moving striation as it passes the point under consideration. The total instantaneous light intensity for the light wavelength is the sum of these two curves. The total intensity did not go to zero at any point (4, 7, 14, 17). The standing striations then maintained constant intensity in the tube while the moving striations passed through them from the direction of the anode to the direction of the cathode.

Further, the variations in the intensity of the moving striations followed that of the standing striations almost exactly but with a smaller amplitude.

Velocities of the positive striations were in agreement with those reported previously in two mm Hg of argon (4, 17). The average velocity varied with tube current (140 m/sec at 11.2 ma to 175 m/sec at 20.5 ma), but it also depended on the particular mode being observed. The velocities measured are summarized in Figure 21.

The positions of occurrence of maximum and minimum velocities were a function of cathode material rather than of the tube current. For a particular electrode combination and mode, the points of maximum and minimum velocities occurred at the same position in the tube for both striations

observed. That is, the motions of both striations were the same as they passed a given position. These variations in velocity, associated with each positive striation's passing down the tube in rapid succession were evidenced at a particular point in the positive column by variations in the light intensity. Velocity maxima appeared a short distance on the anode side of the largest peaks (standing striations) in the light intensity curves and velocity minima appeared a shorter distance to the cathode side of the same peaks. This behavior seemed to apply to all intensity peaks although the limits of experimental accuracy made it difficult to analyze in the cases of the less pronounced peaks of light intensity. It was also noted that velocity minima occurred a short distance to the anode side of each probe. Figure 17 is a graph showing the motion of two positive striations as they pass through the positive column. The intensity curve at the top is of the standing striations existing in the tube. The positions of the standing striations varied with tube current and with cathode.

The standing striations always occurred a short but variable distance to the anode side of the probes. With increasing current the distance from the cathode to the glowing ball increased slightly while the distance from the cathode to the "true" head of the positive column increased markedly. Using a zirconium cathode, molybdenum anode combination, this increase was 0.8 cm between nine and 68.5 ma tube current. While the distance between standing striations varied somewhat between modes during this same increase in current, corresponding standing striations were generally observed to shift toward the anode a distance approximately equal to the increase in distance between the cathode and the "true" head of the positive column. If a mode extended over an appreciable current range, the standing striations

became more diffuse with increased current. If the current was increased rapidly between modes, the standing striations shifted toward the cathode a short distance before shifting a greater distance toward the anode.

The behavior of a positive striation seemed to show that its velocity increased shortly before reaching a standing striation. It then passed through the standing striation, and its velocity reached a minimum just after it passed through the maxima of the standing striation. Each following striation repeated this sequence at the same points in the tube. These velocity changes seem reasonable considering the voltage, field, and electron concentrations along the tube as shown by Emeleus (9) for the case of standing striations.

Donahue and Dieke in postulating their theory reported that the velocity of the moving striations falls to zero at the positions of stationary striations and in argon at 2.1 mm found that the velocity remains zero for short periods of about 11 microseconds (4). They also reported that the light intensity waveshape broadened and decreased in amplitude at the positions of stationary striations. Neither of these effects was observed although it is possible, as can be seen in Figure 17, that the velocity of the striations fell to zero for intervals of 11 microseconds at some position between experimental points. The light intensity did not fall to zero at any point. It appears that the phenomena observed here was different in some respects from that reported by Donahue and Dieke. No probes were constructed into their tubes.

c. Spectroscopic Observations

By comparison of the motion curves for the two light wavelengths for each electrode combination, it was observed that they very nearly corresponded as shown in Figure 17. It was noted, however, that at almost all positions

the plots for light of 4198, 4200 A° coincided with or occurred earlier than plots for 6937, 6965 A°. Further the points of greatest difference occurred, in most cases, near the points of maximum light intensity. These differences were, however, at the limit of experimental accuracy (about ± 15 microseconds).

In order to investigate the question of phase difference, photographs such as those shown in Figure 22 were taken using the method of Section II.5. Time differences were measured between corresponding peaks of light intensity. Phase differences read were again near the limit of experimental accuracy of the technique, but an examination of phase differences between spectral lines 1-5 and lines 6-10 of Figure 20 indicated that in most cases light from one of the red lines (6-10) occurred later than light from one of the blue lines (1-5), all lines having approximately the same ground level. Additional readings comparing only 4198, 4200 A° and 7503 A° indicated again that the component of a positive striation emitting 7503 A° occurred later than that emitting 4198, 4200 A°. This was generally true at the position of maximum light intensity. There was little measurable phase difference at a position of minimum light intensity. The phase difference where it existed was of approximately four to 16 microseconds.

These indications are considered strong but quantitatively inconclusive because of the limitations of the equipment in measuring the small time differences between the argon lines and the difficulty experienced in obtaining consistently clear photographs. In most cases (21 out of 24), however, the phase differences were read showing either no phase difference or the atoms having a higher state of excitation leading atoms having a lower excitation potential.

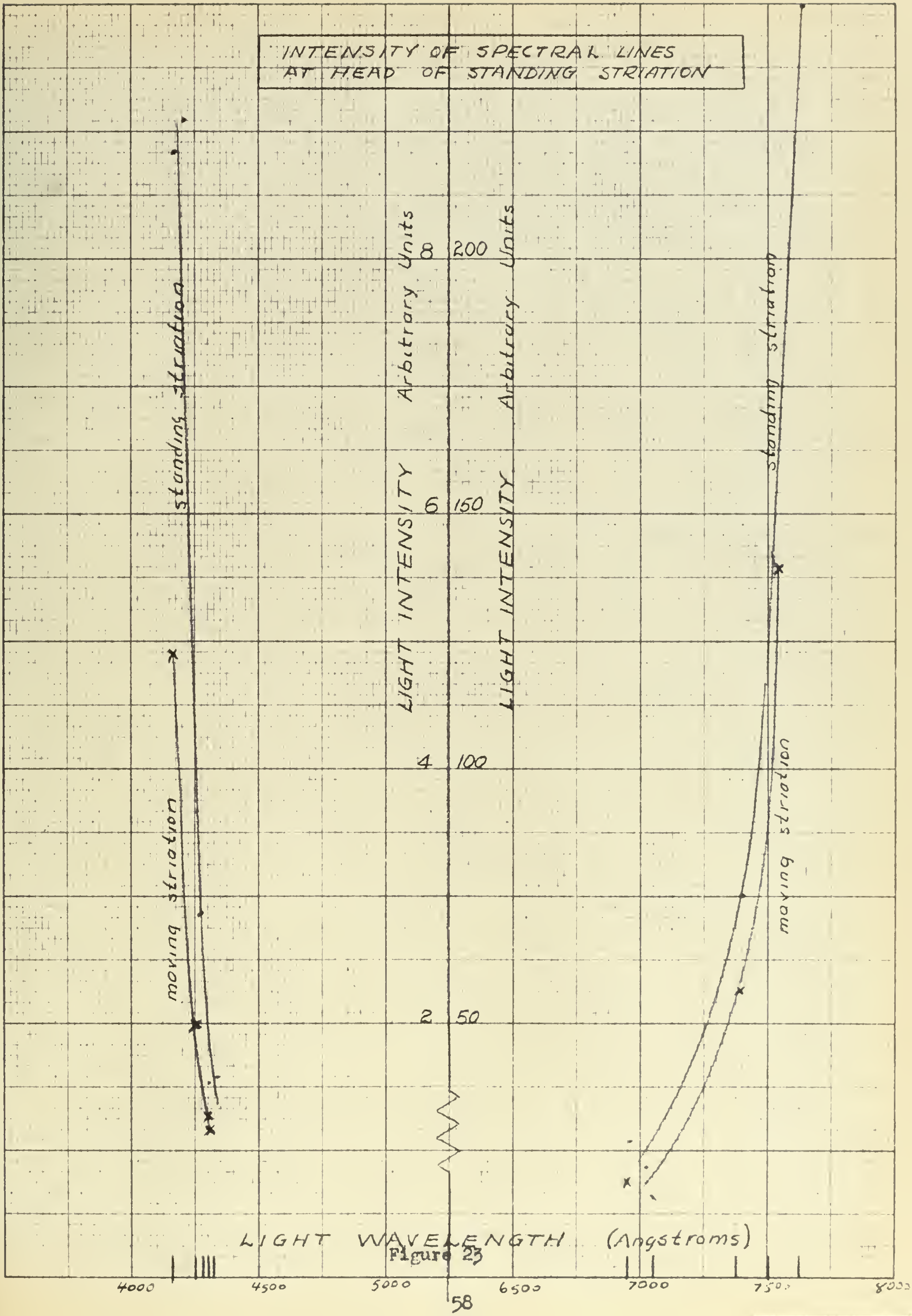
Kolkhorst and Strong (14) working with argon and Donahue and Dieke (4, 7) working with mercury found that atoms having a lower excitation potential emit ahead of those atoms having a higher state of excitation by about 15 microseconds.

The indication here is that the opposite is the case in the maximum of a standing striation and that there is little if any phase difference in the minimum between standing striations. While it might be expected that earlier observations for the moving striations alone should be similar to these results, this need not be true for the type of standing striations in which the observations here reported were made.

Any possible explanation in terms of the Donahue and Dieke hypothesis would seem to be in the possibility of a metastable energy level very near the excited state of the 4198, 4200 A^{o} lines as compared to the metastables of approximately 11 volts which are a possible source of the 7503 A^{o} line.

In analysing these observations the probability of the occurrence of various spectral lines as a function of the energy of the exciting particles must be considered. Observations were not sufficiently complete for such an analysis.

The intensity of the various wavelengths was also observed at three points in the positive column (maximum intensity, minimum intensity, and intermediate intensity). These readings were corrected for the sensitivity of the optical system by means of the calibration curve described in Section II.5. The intensity in arbitrary units was plotted against wavelengths between 4000 A^{o} and 7500 A^{o} as shown in Figure 23 for the position of maximum intensity. Curves for the other two positions were similar except for a difference in intensity. By far the greatest light energy emitted by the positive column at these three points had a wavelength



INTENSITY OF SPECTRAL LINES
AT HEAD OF STANDING STRIATION
LIGHT INTENSITY Arbitrary Units
LIGHT INTENSITY Arbitrary Units
8
200
6
150
4
100
2
50
standing striation
moving striation
standing striation
moving striation
LIGHT WAVELENGTH (Angstroms)
4000
4500
5000
6500
7000
7500
8000

Figure 23

above 6900 Å, the scale of the right ordinate being 25 times that of the left ordinate. The greatest amount of light energy in the range between 4000 Å and 7500 Å came from transitions from energy levels between 13.33 and 13.17 volts to the 4S levels whereas relatively little of the energy came from transitions from energy levels between 14.53 and 14.68 volts to the same levels.

Figure 19 shows the variations in light intensity along the positive column for two different light wavelengths. The scale of arbitrary intensity units for the 6937, 6965 Å light is 7.2 times that of the 4198, 4200 Å light. The amplitude ratio of these intensities varied for various electrode combinations as shown in Figure 21.

These observations, therefore, indicate a greater population of particles excited to the lower energy states between 13.33 and 13.17 volts. Considering a Maxwellian (25) or Druyvesteyn (24) electron energy distribution, it seems reasonable that there should be more excitation to the lower energy states than to the higher.

Comparisons of intensity of the various light wavelengths at the three positions in the positive column indicated that the following wavelengths were appreciably more intense at the point of maximum intensity compared to the point of minimum intensity: 7635, 6937-6965, 4158-4164Å. The following wavelengths showed no appreciable difference in intensity between the three positions: 7503, 7383, 4333-4335, 4300, 4272, 4198-4200.Å. The above comparisons held generally for both moving and standing striations. These results show no particular pattern with respect to excitation energy.

These findings are inconclusive. Further investigation should be profitable in determining the distribution of excited particles and energies within various striations.

d. Periodicity

There was a definite indication of periodicity although it is believed that the presence of probes in the tube interfered with this phenomenon. In the cases observed, the positive striation wavelengths were approximately 6.5 cm. In each case the distances between velocity maxima were approximately equal, the distance varying from 2.0 to 3.4 cm. As noted previously the velocity maxima preceded the passage of a moving striation through the maxima of the standing striations while the velocity minima occurred shortly following the passage of the moving striations through the maxima.

Because of the relation between maximum and minimum positive striation velocities and light intensity maxima, these characteristics occurred together quite regularly along the tube. Considering Figure 17, if the motion curve had a greater slope than shown (decrease in average striation velocity) the points of maximum and minimum velocity and consequently the points of maximum intensity would occur closer together in the tube. The reverse would occur for a decrease in slope (increase in velocity). The action may be the reverse of this, of course, the standing striations being formed first causing the variations in positive striation velocities.

A minimum positive striation velocity occurred just to the anode side of each probe location. There was then a light intensity maximum just to the anode side of each of these velocity minima. This has been noted recently also by Oleson and Cooper (17). These light intensity maxima were somewhat more pronounced than others, the intensity maximum to the anode side of the center probe being the brightest in each case.

It seems possible that each obstruction in the tube caused a decrease in velocity of the striations resulting in an accumulation of ions and an increase in light intensity.

The observation of Donahue and Dieke (4, 7) that $\lambda = nd_s$

where λ = distance between moving striations

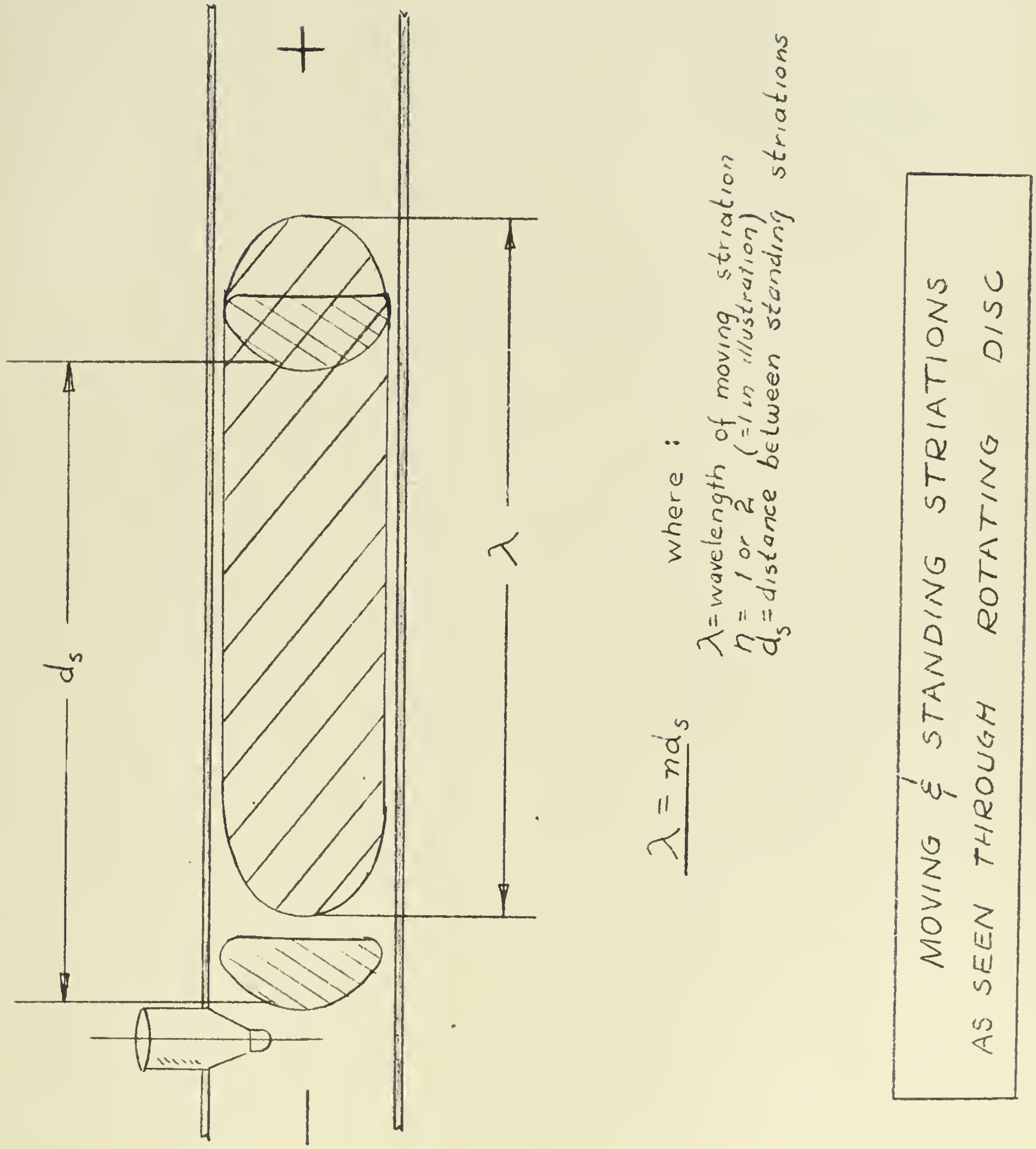
d_s = distance between standing striations

n = an integer, usually one or two

was repeated. This was shown from the motion and intensity vs. distance from cathode curves and by visual observations of the positive column with the rotating disc. A moving striation could be seen, in most cases, to have a wavelength equal to either one or two times the distance between standing striations ($n = 1$ or 2). Figure 24 is a sketch where $n = 1$.

e. Effect of a Magnetic Field

When a permanent magnet was placed with it poles in a vertical plane 1.5 cm to the anode side of the center probe, it was seen that the glow was displaced radially and became more narrow and concentrated in the region 1.0 to 1.5 cm to the anode side of the magnet and that the intensity of the standing striation in that region became greater. This effect is shown in Figure 17 for motion and light intensity by the experimental points shown as squares. Outside of the field of the magnet the curve for the striation had the same form as the other curves shown. The magnet had the apparent effect of decreasing the velocity of the positive striations shortly before they reached the position of the magnet. The apparent decrease in velocity resulted in a considerable increase in light intensity at that point due, evidently, to the increase in concentration of the ions.



MOVING & STANDING STRIATIONS
AS SEEN THROUGH ROTATING DISC
λ = nd_s
where :
λ = wavelength of moving striation
n = 1 or 2 (=1 in illustration)
d_s = distance between standing striations
d_s
λ
+

Figure 24

In this case if the positive ions enter the magnetic field $\vec{B}$ with a velocity $\vec{v}$ parallel to the axis of the tube, a force $\vec{F}$ will be exerted on the ions such that they will have a radial component of velocity in accordance with

$$\vec{F} = q\ (\vec{v} \times \vec{B})\ .$$

If the magnitude of the velocity remains unaltered, the axial component of the ions will be decreased and effects noted would follow.

This action of apparent decreased positive striation velocity and increased light intensity was similar to that observed where the tube was obstructed by a probe.

V. CONCLUSIONS

1. Discussion of Principal Results

It appears that unusual systems of striations occurred in the discharge tube described here. That is, there existed a series of standing striations, the intensity of which remained constant at each point in the tube. These were somewhat similar to those which have been described (6) for diatomic gases. To this system there was added a system of moving striations.

To summarize the events in the tube, standing striations exist emitting an unvarying light. A positive striation leaves the anode in some phase relationship with the voltage. It passes through the tube increasing in velocity when approaching a maximum of a standing striation. The light intensity of the moving striation varies with that of the standing striation, but its amplitude is less than that of the standing striation. The velocity of the moving striation decreases very shortly after passing through the maximum of the standing striation. This sequence is repeated for the next standing striation, the intensity of light from the moving striation always varying with that of the standing striation but with smaller amplitude, and the velocity of the moving striation increasing and decreasing as the maxima of standing striations are reached and passed. Additional positive moving striations follow.

It is possible, of course, that the positive moving striations are established before the standing striations and that the standing striations are formed by the motion of the moving striations, the standing striations being formed by an accumulation of excited particles at the anode side of the positions of low moving striation velocity. Evidence for this postu-

late is that the distance between standing striations seems to depend on the average velocity of the moving striations and the distance between their minimum velocities. The intervals of low striation velocity may be characteristics of the striation, or they may be the result of tube obstructions and discontinuities in the tube wall.

A probe or a magnet appears to cause a decrease in the axial component of striation velocity as explained in Section IV. This decrease may possibly lead to a "backing up" of the particles and a standing striation. The probe or obstruction may thus account for the establishment of the standing striations or may, at least, influence the distance between the standing striations.

It is not possible to state which occurs first, the standing or the moving striations. They could both be formed independently, but in any case they seem to interact and become related.

It is possible that the moving striations, although their action is superimposed on that of the standing striations, follow Donahue and Dieke's hypothesis (4, 7). The data can be interpreted such that the steady light emitted by the standing striation system accounts for the failure of the positive striation light intensity to go to zero between striations. However, light intensity did not go to zero at 12 mm pressure when moving but no standing striations were observed.

Experimental data was not accurate enough to detect zero velocities for periods as short as 11 microseconds. If these points of zero velocity did occur, it would not be necessary that stationary striations be seen at these positions of zero velocity because the standing striation just to the anode side of this point would have a greater intensity and the time

average of intensity of the joined positive and negative striations would be small because of the short 11 microsecond interval.

Interpreted in this way then the only point of difference is that the maxima of positive striation velocity in this case occur prior to, rather than at, the maxima of positive striation intensity as described by Donahue and Dieke.

If, as indicated, the atoms having a higher excitation potential travel ahead of those having a lower excitation potential, this behavior might be associated with the standing striation component rather than with the moving striation component inasmuch as it was most striking at a standing striation, and may, therefore, be an effect not noted previously.

It is of interest that the cathode exerts a strong effect on the behavior of the positive striations in a gaseous discharge, the anode having no appreciable effect. Thus, although the positive striation originates in the region of the anode, it is the cathode and/or the cathode region which determines its properties.

All discussions in this paper concern only the parameters described. In particular the tube is of unique shape and correlation of empirical observations obtained here with those obtained using any other tubes may be difficult.

2. Recommendations for Further Work

Many possibilities exist for further profitable work. Suggestions for using the present tube are:

a. Obtain probe field measurements in the region of the standing striations.

b. Observe visually and photographically the striations using rotating disc, stroboscopic, and rotating mirror techniques.

Measure wavelengths and velocities at all combination of electrodes and at various modes.

c. Consider refinements in optical system to permit more accuracy in spectroscopic observations for phase differences and intensity of various lines as function of position in positive column.

d. Attempt correlation of moving and standing striation frequency, location, and amplitude with similar functions of the ultra high frequencies (radar range) and radio frequencies of the plasma.

To attempt repetition and extension of some of this work with a tube of more regular geometry should be valuable if it is possible to obtain the standing striations. In particular:

a. Observe effects of varying interelectrode distance.

b. At same time take probe measurements in region of standing striations.

c. Study region of cathode particularly in an attempt to observe and correlate negative striations.

3. Acknowledgements

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